PSYCHOPHYSICAL RESPONSES TO EARTH-VERTICAL ROTATIONS IN THE ELDERLY

Capstone Project

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By

MEGHAN M. HISS

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Capstone Committee: Approved by

Julie Hazelbaker, Ph.D., Advisor

Christina M. Roup, Ph.D.

Eric Bielefeld, Ph.D.

Advisor

ABSTRACT

A growing elderly population is vulnerable to injury or death due to falls. Previous studies documenting the physiologic changes that occur within the vestibular system due to the aging process have shown moderate decreases in caloric and rotational chair responses. Psychophysical testing, which has proven to be critical to understanding the function of the auditory and other sensory systems, has not yet been used to study vestibular function in the elderly. The present study had two goals: to determine if psychophysical thresholds correlate with performance on standard tests of vestibular function, and to determine if older subjects have poorer vestibular psychophysical thresholds than younger subjects.

Eighteen older adults (age range 63-84 years) and thirteen younger adults (age range 20-25 years) participated in the study. Psychophysical testing of vestibular function consisted of rotations about the earth-vertical axis to determine both detection thresholds and discrimination thresholds to angular velocity. Standard tests of vestibular function included sinusoidal harmonic oscillation, steps of velocity, and caloric testing.

On average, older adults performed more poorly on psychophysical tests than their younger counterparts. The best older adults did as well as the best younger subjects on both detection and discrimination tasks, but the worst older adults were far poorer than the worst younger subjects. Psychophysical thresholds did not correspond to performance on rotational chair testing. These results demonstrate that normal older adults have a wider performance range than younger subjects on psychophysical testing. It also indicates that psychophysical testing accesses different information than standard tests of vestibular function. This suggests that psychophysical testing may be an important additional method for measuring balance function in the elderly.

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VITA

JUNE 17, 1986. . . . . Born in Columbus, Ohio

MAY 2004. . . . . …..Graduated from West Jefferson High School

JUNE 2008. . . . . …..B.A. Speech and Hearing Science with Research Distinction, The Ohio State University

FIELDS OF STUDY

Major Field: Audiology

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LIST OF ABBREVIATIONS

ASHA	American Speech-Language Hearing Association
BPPV	benign paroxysmal positional vertigo
CDC	Center for Disease Control
CDP	computerized dynamic posturography
deg/sec	degrees per second
ENG	electronystagmography
ENT	otolaryngologist
Hz	hertz
MCT	motor control test
SCM	sternocleidomastoid muscle
SD	standard deviation
SHA	sinusoidal harmonic acceleration
SISI	short increment sensitivity index
SOT	sensory organization test
VCR	vestibulocollic reflex
VEMP	vestibular-evoked myogenic potential
VNG	videonystagmography

VOG	video-oculography
VOR	vestibulo-ocular reflex
VSR	vestibulo-spinal reflex
VST	velocity step test

CHAPTER 1

Introduction

Incidence/Prevalence of Falls

A growing elderly population is vulnerable to injury or death due to falls. Each year, one in every three adults age 65 years or older will fall and two million will be treated in an emergency department for injuries caused by falls [Center for Disease Control (CDC), 2010; Hausdorff, Rios, & Edelber, 2001]. Falls can lead to injuries, such as hip fractures and head traumas, and can even increase the risk of early death. According to the CDC, over 18,000 older adults died in 2007 from fall injuries. Additionally, the susceptibility to falls and related injuries only increases when older adults in nursing homes are taken into consideration (CDC, 2009). Also, with the growing elderly population, these numbers are likely to increase as the Baby Boomer generation reaches age 65 years. Falls in the older adult population have been associated with dizziness, balance disorders, and vestibular dysfunction (Agrawal, Carey, Della Santina, Schubert, & Minor, 2009; Alrwaily & Whitney, 2011). Research has also demonstrated a decline in quality of life in older adults who experience dizziness (Hsu, Hu, Wong, Wang, Luk, & Chern, 2005). As evidenced by the aforementioned statistics, research regarding imbalance in older adults is critical to better understanding falls and developing future treatment plans for the prevention of falls.

Anatomy and Physiology

The vestibular system is integral to maintaining balance control. The vestibular sensory organs of the inner ear respond to physical stimuli related to movement and orientation of the head in three-dimensional space (Wright & Schwade, 2007). During movement, information is gathered through visual, somatosensory, and vestibular senses and sent to the brain for integration and perception processing (Desmond, 2004). These senses help maintain clear vision during head movement, control muscles responsible for maintaining body posture, and provide a sense of orientation with respect to the surrounding environment (Wright & Schwade, 2007). The paired vestibular organs, housed in the temporal bone, are comprised of three semicircular canals (superior, posterior, and horizontal) and two otolith organs (the utricle and saccule). The three semicircular canals contain sensory receptors, which are stimulated by forces associated with acceleration, and are oriented at different angles with respect to the vertical and horizontal planes. The superior and posterior semicircular canals are oriented vertically, whereas the horizontal canal is tilted upward by 30 degrees in the horizontal plane. Ultimately, this allows the vestibular system to encode a variety of head movements in different spatial planes (Wright & Schwade, 2007). The saccule and utricle, on the other hand, are functionally distinct from the semicircular canals in that they are sensitive to linear acceleration and gravitational force. Because these structures are sensitive to gravitational force, their receptors are always active and monitor the position of the head in space, even when there is no head movement. This is in direct contrast to the normal functioning of the semicircular canals because their receptors do not typically respond to static head position. The macula sacculi are sensory neuroepithelium housed in the saccule and are predominantly oriented in the vertical plane (Watanuki & Schuknecht, 1976). Due to their position, the macula sacculi are the most sensitive to up-and-down movements of the head and horizontal motion along the front-to-back axis. Conversely, the utricular macula is situated in the superior portion of the utricle and lies in the horizontal plane. This orientation makes the utricular macula most sensitive to linear movements.

Similar to the auditory system, the vestibular system also contains hair cells that have their own unique functions. As previously mentioned, the semicircular canals and otolith organs are sensitive to different head motions and gravitational forces. In the auditory system, hair cells are stimulated by sound waves, however, in the vestibular system, hair cells are stimulated by movement and gravity (Desmond, 2004). Each vestibular hair cell has one kinocilium and several stereocilia (Wright & Schwade, 2007). The stereocilia are arranged in several rows that increase in height across the cell, and has been described as a “stair-step” pattern. The single kinocilium is situated near the tallest row of stereocilia and thus fits in with the aforementioned pattern. Together, the kinocilium and stereocilia of the otolith hair cells project into a sheet of gelatinous material that covers the surface of the neuroepithelium. Contained in this sheet are tiny crystals called otoconia, and with the gelatinous material, make up the otoconial membrane. Oticonia are composed of calcium carbonate in the form of the mineral calcite (Thalmann, Ignatova, Kachar, Ornitz, & Thalmann, 2001). The oticonia differ in size and are arranged in a definite pattern across the oticonial membrane. During the occurrence of linear head movement or gravitational force, the otoconial membrane undergoes small shifts in position, thereby deflecting the cilia on the underlying sensory cells (Wright & Schwade, 2007). This creates changes in the electrical polarization of the hair cells, which in turn, causes the release of neurotransmitters.

All of the aforementioned vestibular neuroepithelia contain sensory cells of two different morphologic types (Lindeman, 1969). The type I receptor cell is a plump, goblet-like shape, and is entirely surrounded by a single, large nerve ending known as the chalice. The type II receptor cells are more slender and cylindrical in shape, and they have clusters of small nerve endings at their basal end. In each vestibular neuroepithelia, groups of these receptor cells are oriented in a manner so that all cells within a group are either depolarized or hyperpolarized by a given movement of the otoconial membrane (Lindeman, 1969). On the cristae of the semicircular ducts, all of the receptor cells are oriented the same manner. In the case of the lateral crista, each hair cell is organized so that its kinocilium is on the side of the cell nearest to the utricle. Therefore, if the head moves in a manner that results in displacement of the lateral crista toward the utricle, the stereocilia will be deflected toward the kinocilia, effectively depolarizing the sensory cells and producing increased neural excitation. Conversely, displacement away from the utricle will result in hyperpolarization of the sensory cells, and will result in a reduction of neural excitation.

Vestibulo-ocular reflex (VOR) and vestibulo-spinal reflex (VSR)

Balance control involves a number of systems that help coordinate the action of trunk and leg muscles in order to minimize sway and maintain the body’s center of mass within its base of support. However, in order to accomplish this task, the body must utilize two vestibulomotor reflexes: the vestibulo-ocular reflex (VOR) and the vestibulospinal reflex (VSR). The VOR can be defined as reflexive eye movement in response to head movement (Desmond, 2004). The role of the VOR is to allow stable gaze while the head is moving. Gaze stabilization is imperative because images need to stay long enough on the retina to be encoded into neural signals (Leigh & Zee, 1991). In order to achieve a steady retinal image during head movement, the information from the peripheral vestibular system is passed to the oculomotor pathways, where compensatory eye movements are generated by moving the eyes with the same velocity but in the opposite direction of the head motion (Baloh & Honrubia, 1990). Ultimately, the VOR is extremely important during vestibular assessment and the VOR function is actually the foundation for many vestibular tests, such as caloric and rotational chair testing.

The VSR, on the other hand, is one of the motor control mechanisms that contribute to postural stability during routine tasks, such as upright standing or walking and more complex tasks, such as running or jumping (Baloh & Honrubia, 1990). In order to achieve this goal, the VSR must constantly receive sensory information about the orientation of all body segments, including the head, neck, torso, and legs. To maintain postural stability, the VSR pathways must detect spatial orientation of all body segments with respect to an earth-fixed frame. In addition to the vestibular system, our sensory systems such as proprioception and vision, supply the VSR with sensory input regarding the orientation of different body parts. Proprioceptive receptors lie in the muscles and joints and provide information about the relative orientation of two adjacent body segments, whereas the visual system provides information about the relative orientation of the body with respect to the external environment. Thus, the VSR incorporates information from various sensory systems in order to distribute information about the earth, vertical to the legs, which allows synchronized reciprocal stabilization of the body (Baloh & Honrubia, 1990).

Standard vestibular tests of balance

Vestibular function tests are an important part of the clinical assessment and management of patients with dizziness and other balance disorders (Goebel, 2001). Assessing vestibular function is unique because there is no direct access to the response of the vestibular end organ. Clinicians must rely on secondary motor responses to assess the vestibular pathways (Baloh & Honrubia, 1990). One of the oldest tests developed to evaluate vestibular function is electronystagmography (ENG). ENG is based on electro-oculography, a technique that objectively records eye movements by measuring the corneoretinal potential (Gans & Yellin, 2007). When the head is rotated, movement of the endolymph causes an individual with normal vestibular function to produce compensatory eye movements away from the fluid motion. The eyes will move slowly until they reach maximum deviation, then return quickly back into position because of central nervous system correction before repeating these compensatory motions. This activity generated by the VOR is identified as nystagmus, which includes both a slow-phase component as well as a fast-phase component. Thus, ENG testing measures these ocular movements to determine if the individual's compensatory eye movement is consistent with normal vestibular function. More recently, however, videonystagmography (VNG) has emerged as a more popular and diagnostically efficient recording method. VNG utilizes infrared video cameras to visualize and record both linear and torsional eye movements. VNG and ENG protocols are essentially the same and therefore, the following information will be described from a VNG test battery standpoint.

Spontaneous nystagmus is usually the first test in the VNG test battery because it needs to be measured early on due to its potential to influence the interpretation of all subsequent test results. Spontaneous nystagmus is involuntary, unprovoked, repetitive eye movement that can appear in any direction (Gans & Yellin, 2007). The presence of spontaneous nystagmus is indicative of pathology occurring within the peripheral or central nervous system (Brandt, 1993); therefore individuals with normal vestibular function will not demonstrate spontaneous nystagmus. Following the spontaneous nystagmus testing, three ocular motor pursuit function tests including saccade, smooth pursuit, and optokinetic testing are next in the VNG test battery. The saccade test evaluates the eyes' ability to shift the point of visual fixation (Evans & Melancon, 1989). In fact, the saccade is the most rapid movement the oculomotor system is capable of performing. To perform the test, the patient is seated upright and asked to face the stimulus. The patient is then asked to follow and fixate, without head movement, on a single target that randomly moves horizontally, vertically, and diagonally, for distances ranging 5 to 20 degrees. Once this testing is completed, latency, velocity, and accuracy of the response are measured through eye motion to determine if vestibular function for this task is normal. Following saccade testing, smooth pursuit, also known as tracking, is performed. Tracking examines the ocular smooth pursuit system. The patient is instructed to fixate, without head movement, on a target moving in a sinusoidal pattern that extends 20 degrees to the right and left from center. Eventually, the target movement progresses from low frequency (slow moving) to high frequency (fast moving). Normal sinusoidal tracking responses are characterized by smooth, sinusoidal movements whose amplitudes correspond to the motion of the target (Gans & Yellin, 2007). The last of the ocular motor pursuit function tests is the optokinetic test, which measures nystagmus elicited by watching repetitive stimulus movement across the visual field. True optokinetic testing can only be measured if the visual field is 80% filled and thus, can only really be accomplished using a stimulus projected on a large screen or presented within an enclosure. To perform this type of testing, the patient is presented with horizontal stimuli moving from right to left for ~20 seconds, then left to right for ~20 seconds. These stimuli are presented at a slow speed (20 degrees/second) and a fast speed (40 degrees/second). The patient is instructed to follow the stimuli, without head movement, from one direction to the other, repeating this until the ~20 seconds have elapsed. Results of optokinetic testing are analyzed for symmetry in each direction of pursuit. If an asymmetry is present, this indicates an abnormal response and can suggest a central abnormality or unilateral peripheral weakness.

The next component of the VNG test battery is the gaze test. The gaze test records any nystagmus that is present when the head is stable and upright, and the eyes are in a fixed position. Unlike the previously mentioned ocular motor pursuit function tests, vision is denied for the gaze test. For this testing, five separate 20 second recordings are captured as the patient fixates at targets placed at 0 degrees azimuth, 20 degrees to the right of center, 20 degrees to the left of center, 20 degrees above center, and 20 degrees below center. If nystagmus is detected in any of those target positions, the test is repeated, at that same target, with vision to see if the vision will suppress the nystagmus. The presence of nystagmus during the gaze test is consistent with numerous peripheral and central nervous system pathologies. In order to identify the site of lesion, the direction of the nystagmus, as well as the nature of the gaze evoked pattern, should be further analyzed.

Following the gaze test, the Dix-Hallpike positioning tests are performed. These tests are designed to elicit nystagmus and subjective vertigo that are caused by benign paroxysmal positional vertigo (BPPV). Several studies have demonstrated an increased incidence of BPPV in older adults (Baloh, Honrubia, & Jacobson, 1987; Neuhauser, Leopold, von Brevern, Arnold, & Lempert, 2001; von Brevern et al., 2007). BPPV is the result of displaced otoconia settling in the posterior semicircular canal, generating a gravity-dependent cupula deflection (Gans & Yellin, 2007). It is important to note that the Dix-Hallpike test evaluates only BPPV as it relates to the posterior semicircular canal. This type of BPPV is the most prevalent due to the location of the posterior semicircular canal, which is just inferior to the utricle.

Testing for BPPV requires the patient's eyes to be open, allowing the tester to directly observe eye movements for nystagmus. Traditionally, the Dix-Hallpike maneuver was performed with the tester standing to the side of the patient, however as this positioning was more cumbersome than useful, a modified Dix-Hallpike maneuver is used more often and will be described (Dix & Hallpike, 1952; Gans & Yellin, 2007). For the modified Dix-Hallpike, the examiner stands behind the patient and the patient is asked to turn his or her head slightly toward the test ear. The examiner then supports the patient's neck and back while the patient is lowered into a supine position. Ultimately, the patient's neck is slightly hyperextended off the examination table, allowing the examiner to clearly observe the patient's eye movements. According to Gans and Yellin

(2007), rapid positioning is not necessary as the provocation of BPPV symptoms is gravity-based and due to changing positions. Once the Dix-Hallpike maneuver is completed, the patient returns to an upright position and the test is repeated with the patient's head turned toward the other ear.

In addition to the Dix-Hallpike positioning tests, further positional nystagmus testing may be performed. The purpose of this type of testing is to determine if nystagmus can be elicited or if previously documented nystagmus can be altered when the head and body are placed in static positions (Gans & Yellin, 2007). It is important for this testing to occur after the Dix-Hallpike maneuver so the BPPV does not contaminate the positional tests as positions are changed. Positional tests require the patient to be placed in the following positions: supine, head/body right, and head/body left. For the head/body positions, the head must be rotated 90 degrees so either ear is perpendicular to the ground. Recordings of eye movement should be measured for 20 seconds in each position with vision denied. If nystagmus is observed in any position, the test should be repeated in the same position with vision enabled. This allows the examiner to determine if nystagmus can be suppressed with vision. If nystagmus has been detected in any position, the direction of the nystagmus is analyzed to determine the cause or location of pathology. For example, if the fast phase of the nystagmus is toward the ground, this is known as geotropic nystagmus, and is most likely the result of a peripheral lesion. Conversely, if the fast phase of the nystagmus is away from the ground, this is known as ageotropic nystagmus, and this is often correlated with central nervous system, pharmacological, or alcohol influences. It is important to remember that nystagmus found in any positional testing should always be correlated with other symptoms reported by the patient, such as vertigo or nausea.

Often considered the most important part of the VNG test battery, bithermal caloric testing is usually the last component performed. One advantage offered by caloric testing is that it specifically isolates and evaluates the ability of each horizontal semicircular canal (Barber & Stockwell, 1980; Gans & Yellin, 2007). By irrigating the external auditory canal with warm or cool air, a temperature change is transmitted to the endolymph in the horizontal semicircular canal (Jacobson & Newman, 1993). This simulates endolymphatic fluid movement, and mimics what happens during head rotation. The use of both warm and cool air creates two different effects in the horizontal semicircular canal and allows the physiological integrity of both horizontal canals to be evaluated separately and compared. Warm air simulation causes ampullopetal movement of the horizontal canal cupula, whereas cool air simulation creates ampullofugal movement of the cupula. Ampullopetal is movement toward the ampulla and ampullofugal is movement away from the ampulla. The effect of these movements is an increase in hair cell activity in the crista, which generates nystagmus. In most cases, the direction of the nystagmus follows a predictable pattern. The expected physiological responses to thermal stimulation are left-beating nystagmus to right cool irrigation, right-beating nystagmus to left cool irrigation, left-beating nystagmus to left warm irrigation, and right-beating nystagmus to right warm irrigation (Gans & Yellin, 2007). To begin caloric testing, it is important to provide the patient with instructions as well as a general overview of the test. Patients should be instructed that each ear will be presented with both a cool and warm temperature stimulus, which will induce a response from the vestibular system. The results of this response can then be measured and analyzed to determine if there is a response and whether or not the response is equal from both ears. Patients should be informed that testing will begin with a cool stimulus to the right ear, then to the left ear, followed by a warm stimulus to the left ear, and ending with one to the right ear. A five to ten minute break will occur between each stimulus, in order to let the inner ear fluids return to their normal homeostatic temperature. This helps to prevent potential confounding variables that can occur from inducing a temperature change in the inner ear fluids. Additionally, the patient should be cautioned that caloric testing may induce a spinning or floating sensation.

To begin testing, the patient is placed in a supine position with the head elevated and resting at a 30 degree angle (Gans & Yellin, 2007). Covered goggles are placed on the patient's face and the patient is asked to keep his or her eyes wide open throughout the duration of testing. Prior to caloric stimulation, eye recordings should be made to observe for any spontaneous nystagmus the patient may have. Following this, the tester presents the first caloric stimulation. There are two different irrigators available for caloric stimulation. One option is a water irrigator, which consists of two baths containing warm and cool water, a temperature sensing device, thermostats to heat the water, a switch that controls water flow, and a delivery system that presents the water to the ear canal. The second type of irrigator system is the air irrigator. The air irrigator consists of an air flow regulator, a heater, a thermostat, and a hose or speculum that delivers the air to the ear canal. One difference between the two irrigator options is the temperatures of the cool and warm stimuli. Water irrigations are performed at 30 and 44 degrees Celsius, while air irrigations are performed at 24 and 50 degrees Celsius (Gans &

Yellin, 2007). Another difference is the length of time required for air irrigations versus water irrigations. For air irrigations, the stimulus should be presented to the patient for approximately 60 seconds, whereas the time length for water irrigations is approximately 30 seconds. Regardless of the type of irrigator used, it is important for the tester to ensure that the stimulus is delivered appropriately and effectively to the patient's ear canal. Once the stimulus has been delivered, the patient maintains his or her position with eyes wide open and the patient's eye movements are then recorded. Typically, a fixation light inside the goggles is set to turn on 40 seconds after the irrigation has ceased, which is around the time the nystagmus has reached its peak amplitude. Once the patient has fixated, the recording stops and the patient is able to relax until the presentation of the next stimulus. This process is then repeated for the subsequent irrigations. Once the tester has compiled all of the eye recordings, an analysis can be performed to determine vestibular function. Right ear responses are compared to left ear responses to determine unilateral weakness, while right-beating nystagmus is compared to left-beating nystagmus to determine directional preponderance (Gans & Roberts, 2006). These results can be used to identify many vestibular abnormalities, such as a peripheral lesion, a central nervous system disorder, or brainstem or cerebellar disease (Evans & Melacon, 1989; Jacobson, Newman, & Peterson, 1993).

In addition to VNG testing, rotational chair testing is another clinical test used to measure vestibular function. Rotational chair testing was developed to test VOR function occurring during normal active movements at frequencies of 2 to 6 Hz (Fineberg, O'Leary, & Davis, 1987). Although VNG testing also tests the VOR, it is limited because it is only able to assess horizontal canal function at an extremely low frequency of 0.003 Hz (Gans & Yellin, 2007). Therefore, rotational chair testing was developed to assess horizontal canal function at higher frequencies, such as those between 2 to 6 Hz, in order to detect possible high frequency vestibular lesions. Unlike caloric testing, rotational chair testing is not used as commonly for multiple reasons. One reason is because during rotational chair testing, both labyrinths are tested simultaneously, which prevents ear-specific information and makes it more difficult to obtain unequivocal side-of-lesion data. Secondly, rotational chair testing requires the installation of expensive equipment that cannot be easily moved. This equipment includes a specialized computer system, a darkened enclosure, and a rotational chair.

Preparation for patients should occur in a dark enclosure where the testing will occur. This allows the patients' eyes to begin dark-adapting. The patient should be secured in the rotational chair with some type of constraint, such as a seatbelt or harness. Additionally, it is important to secure the patient's feet, knees, torso, and head, so as not to introduce any confounding variables into the test. The patient's head should be tilted down approximately 30 degrees to place the horizontal semicircular canals parallel to the floor and perpendicular to the axis of rotation (Brey, McPherson, & Lynch, 2008). Similar to VNG testing, rotational chair testing also measures and analyzes eye recordings to determine if there are any vestibular abnormalities. In order to record and monitor eye movements from outside the test enclosure, patients should be fit with goggles that contain infrared cameras, such as video-oculography (VOG). Patients should be informed that there is a talk-back system that allows the tester to always be in communication with the patient.

Once the patient is properly secured and the infrared cameras are ready to record eye movements, the tester should calibrate the equipment. The calibration is used to determine the eye recording system's output for a given deviation of the patient's eyes when fixating on visual targets at predetermined distances from the midline (Brey et al., 2008). Calibration helps to ensure that proper eye position recording techniques are being utilized. In most rotational chair test batteries, the calibration is usually performed using saccadic eye movement targets at plus or minus 10 degrees from midline, or a smooth pursuit test target presented at approximately .16 Hz. Following calibration and similar to VNG testing protocol, the patient's eye movements should be observed for spontaneous nystagmus prior to the administration of any rotational chair tests. To test for spontaneous nystagmus, the patient stares at a laser target in the darkened enclosure for approximately 10 seconds. After 10 seconds, the target disappears and the patient is instructed to stare as if the target is still in place for 30 seconds. Eye movements are recorded during the 30 seconds and are analyzed for any spontaneous nystagmus.

The first test and one of the more common tests utilized in rotational chair test batteries is the sinusoidal harmonic acceleration (SHA) test. The SHA test assesses balance function by measuring nystagmus produced in response to back-and-forth sinusoidal movement generated by the rotational chair (Gans & Yellin, 2007). SHA testing simulates natural environmental motion to measure vestibular function, and for this reason, has become a vital component of balance function evaluations. Similar to VNG testing, it is important to provide patients with instructions regarding the test protocol. Prior to SHA testing, the patient should be informed that the chair will be rotated at several different speeds, with a short rest period in between speeds. The first rotation will be very slow and the chair will rotate 360 degrees in both directions. The chair rotations will become progressively faster and the last rotation will result in a back-and-forth sinusoidal motion. The patient should be instructed to relax as much as possible and to keep his or her eyes open throughout the duration of testing. It is helpful to the tester if he or she provides the patient with alerting tasks. By providing the patient with alerting tasks, this ensures that the patient's nystagmic response is not suppressed.

In order to evaluate vestibular output over a wide range of frequencies, SHA testing usually incorporates a minimum of five test frequencies. The following frequencies are commonly used during SHA testing: 0.01, 0.02, 0.04, 0.08, 0.16, 0.32, and 0.64 Hz (Brey et al., 2008; Hirsch, 1986). Once the patient has been tested with at least five of the aforementioned frequencies, fixation testing is performed (Gans & Yellin, 2007). For this testing, the chair is again rotated at the two highest frequencies of rotation, usually at 0.32 and 0.64 Hz. The patient is instructed to fixate on a light located at eye level in the patient's visual field. During this, mental alert tasks are not performed because the goal of this test is to see whether or not the nystagmus can be suppressed. Once SHA testing is completed, the patient's eye recordings are analyzed and the parameters of phase, gain, and asymmetry are examined (Li, Hooper, & Cousins, 1991). The analysis of these parameters helps provide information on whether vestibular function is normal, or in the case of vestibular abnormalities, the location of these abnormalities. For example, phase abnormalities represent differences in the start of the stimulus (head movement in response to chair rotation) and when the patient's compensatory eye movements occur (Gans & Yellin, 2007). It has been found that most peripheral vestibular disorders have been associated with phase abnormalities as measured by rotational chair testing (Hirsch, 1986; Li et al., 1991). Additionally, gain measurements provide information on the amplitude of eye movements that occur in response to head movement, and which depend on the velocity of rotation. Low gain measurements may be representative of bilateral chronic vestibular weakness, whereas increased gain can be associated with central nervous system injury (Baloh, Yee, Kimm, & Honrubia, 1981). And lastly, the measurement of symmetry evaluates and compares clockwise and counterclockwise nystagmus. When the chair is rotated in the clockwise direction, counterclockwise eye movements are generated, while rotations in the counterclockwise direction lead to clockwise eye movements. In the earliest stages of acute, peripheral lesions, a significant asymmetry will be observed (Gans & Yellin, 2007). This asymmetry, however, is only present in the earliest stages of the lesion due to vestibular compensation occurring over time. Additionally, patients with central lesions demonstrate persistent low-level asymmetry (Hamid, Hughes, Kinney, & Hanson, 1986). As evidenced by the previous information, SHA testing is an important component of the vestibular test battery as it can assist in finding vestibular deficits, particularly those at higher frequencies, that standard VNG testing cannot identify.

Another rotational chair test commonly utilized in the vestibular test battery is the velocity step test (VST). VST measures the decay rate of nystagmus following an abrupt angular acceleration or deceleration (Brey et al., 2008). This decay is defined as the time required for the nystagmus to reduce to 37% of its maximum value. Similar to SHA testing, eye movements are recorded and analyzed. Patients should be instructed that the chair will rotate in one direction, clockwise or counterclockwise, for approximately 45-60 seconds. At the end of this time window, the chair will abruptly decelerate and movement will cease. During this time, the patient's eye movements will be recorded for another 30-60 seconds. It is important to instruct the patient keep his or her eyes wide open even after the chair stops rotating. Once the eye movements have been recorded, the test is repeated in the opposite direction. Lastly, similar to SHA testing, VST can also include a fixation test to determine if the nystagmus can be suppressed following rotational stimulation. Following the VST, information about gain, asymmetry, and time constants are obtained through analyses to determine vestibular abnormality (Handelsman & Shepard, 2008). For instance, when time constants are lower than normal, this indicates an abnormality in the velocity storage mechanism, which is most consistent with peripheral involvement. Additionally, symmetry can be analyzed to determine if one rotational direction produces stronger nystagmus than another. If this is the case and an asymmetry is noted, it is possible to determine which peripheral system has the abnormality based on the direction and gain of the nystagmus. Similar to SHA testing, the VST has the advantage of testing the vestibular system at higher velocities and frequencies than the VNG test.

One test that is often times performed in the VNG test battery, but in actuality should be performed with a rotational chair is the optokinetic test. As previously mentioned, the only way to truly test the optokinetic pursuit system is in a darkened enclosure with a rotational chair. The reason for this is because this type of enclosure is the only environment that will produce the patient's sensation of turning (Brey et al., 2008). However, because this is routinely measured during VNG testing, it is not often utilized with a rotational chair. If performed during rotational chair testing, the test is carried out with the patient's chair fixed and pointed away from the door of the enclosure.

A rotating visual stimulus is projected on the wall from a sphere or drum above the patient's head. Stimuli are presented horizontally from right to left for approximately 20 seconds and then left to right for the same amount of time. The stimuli are presented at a slow speed of 20 degrees per second and a fast speed of 40 degrees per second (Gans & Yellin, 2007). The patient is encouraged to keep his or her eyes wide open and eye movements are recorded throughout the duration of the test. Results of the eye movements are then analyzed for symmetry in each pursuit direction. If an asymmetry is observed, this may be indicative of a central nervous system abnormality or a peripheral lesion when the stimulus moves in the direction of an uncompensated or active unilateral weakness (Leigh & Zee, 1991). As evidenced by the previous information, optokinetic testing is a useful test in a vestibular test battery, regardless of how it is performed. That being said, it really should be performed within the rotational chair test battery as it more accurately tests the optokinetic reflex. When testing this reflex with only a light bar, it actually becomes a visual tracking test, rather than an optokinetic pursuit test (Brey et al., 2008). Therefore, to ensure best practice during vestibular testing, optokinetic testing should be performed within the rotational chair test battery.

Vestibular-evoked myogenic potential (VEMP) testing and computerized dynamic posturography (CDP) are two additional tests that can be performed as part of a vestibular test battery. While these tests are typically not performed on a routine basis, simply due to both requiring specialized equipment, they still provide useful information regarding vestibular system function when utilized. VEMP testing focuses on the vestibulocollic reflex (VCR), which is located between the saccule otolith organ and the sternocleidomastoid (SCM) muscle (Gans & Yellin, 2007). Essentially, VEMP testing reflects vestibular system activity that is elicited by high intensity sounds and is measured as a change in muscle potentials within the neck (Hall, 2007). One advantage of utilizing VEMP testing is the ability to detect lesions in the saccule, inferior vestibular nerve, and the lower brainstem (Gans & Yellin, 2007). VEMP testing involves placing electrodes on the patient's forehead and on the patient's SCM muscles in order to record a response. While there is much variation among laboratories in terms of electrode placement and VEMP protocol, the important component is to ensure proper electrode placement so as to maximize the response of the SCM muscle contraction. Additionally, some laboratories will have patient's lie in a supine position and raise his or her head to contract the SCM muscle, while other facilities will simply have the person sit upright and turn his or her head to contract the muscle. Regardless of which method is used, the focus should be on maximizing muscle tension in order to record a robust response. An acoustic stimulus, usually a click or tone burst, is presented to the patient via insert earphones or traditional headphones. Stimulus intensity levels used during VEMP testing are usually 95 to 100 dB nHL. However, with certain disorders, such as superior semicircular canal dehiscence, intensity levels can be as low as 70 to 75 dB nHL (Brantberg, Bergenius, & Tribukait, 1999). When recording the right SCM muscle response, the acoustic stimulus is presented to the right ear while the patient turns his or her head left to properly contract the right SCM muscle. When recording the left SCM muscle response, the auditory stimulus is presented to the left ear and the patient turns his or her head to the right. Once muscle responses have been obtained for each SCM, results can be analyzed for abnormalities. Analysis of the VEMP is typically based on latency or amplitude. Additionally, the VEMP test has an advantage over other evoked potentials as it is a robust response with clearly definable P13 and N23 components (Gans & Yellin, 2007). The P13 and N23 components refer to the pattern of the VEMP response with a positive peak in the 13 millisecond latency region and then a negative trough at approximately 23 milliseconds (Hall, 2007). Also, because the VEMP test is unique in its ability to evaluate the VCR pathway, it provides useful diagnostic information on both otologic and neurologic conditions, such as Meniere's disease, vestibular neuritis, multiple sclerosis, and cerebellar disease (Shimizu, Murofushi, Sakurai, & Halmagyi, 2000; Zapala & Brey, 2004).

CDP is a test of balance function that assesses the patient's ability to use sensory input to coordinate motor responses (Nasher & Peters, 1990). While the majority of the previous vestibular tests focus on peripheral and central components of the vestibulo-ocular system, CDP evaluates an individual's ability to utilize information from the visual, vestibular, and somatosensory systems, both individually and together, to coordinate motor responses to maintain balance (Nasher, 1971). Results from CDP provide unique information that can be compared with other tests of balance function to qualitatively determine the nature of a balance disorder (Nasher & Peters, 1990). In order to perform CDP, the patient must be able to stand upright and unassisted with eyes open for periods of at least one minute (Gans & Yellin, 2007). Additionally, the patient should be informed that CDP is a test of balance that is evaluated with a movement-sensitive platform, and at times, the platform and visual surround will move and thus, cause the patient to move. The patient should also be instructed that CDP has multiple subtests and that each one is more challenging than the prior one.

Preparation for CDP includes fitting the patient with a safety harness that connects to an overhead bar (Gans & Yellin, 2007). The harness should be fit appropriately to the patient so that the patient's weight is transferred through the patient's lower trunk and so that the patient still has freedom of motion. If the overhead straps are too tight, this could assist the patient in remaining upright and bias the results of the test. Once the patient has been fit with the harness, the next step involves positioning the patient's feet on the platform. Proper alignment involves directly centering the medial malleolus of the ankle joint over a marking stripe that transects the two footplates. Once the patient's feet have been properly aligned, testing may commence.

As previously mentioned, CDP has several subtests and these subtests are divided into two parts: the sensory organization test (SOT) and the motor control test (MCT) (Hunter & Balzer, 1991). The SOT is comprised of six conditions that assess the patient's ability to integrate correct sensory information, while ignoring erroneous sensory cues (Gans & Yellin, 2007). Condition 1, which is the easiest condition, involves the patient standing on the force plate with eyes open. Condition 2 is essentially the same as condition 1, however the patient's eyes are closed and thus visual information is eliminated. Condition 3 has the patient's eyes open and the force plate stable, however the visual surround moves and provides inaccurate visual input. In condition 4, the patient's eyes are open and the visual surround is stable, however the support surface moves providing the patient with inaccurate proprioceptive cues. For condition 5, the eyes are closed and the force plate moves. This eliminates visual and somatosensory information and ensures that the patient is completely dependent on his or her vestibular system. In condition 6, eyes are open and both the force plate and visual surround move.

Once again, the patient is forced to rely on vestibular information as inaccurate visual and somatosensory cues are being introduced to the patient. Ultimately, the patient is assessed in each condition with three separate 20 second trials.

In addition to the SOT subtests, CDP also includes the MCT, which evaluates the patient's responses to perturbations of the force plate (Gans & Yellin, 2007). Two types of perturbations are used. The first part of the test introduces random small, medium, and large forward-and-backward translations in the horizontal direction. This is dependent on the patient's height and the goal is to evaluate the patient's ability to adapt to these rapid and abrupt movements. The second part evaluates the patient's ability to adapt when the support surface is shifted to an angle and the foot plate forces the toes upward or downward. Three presentations of each translation stimulus are performed and results are averaged to characterize an accurate response.

Once the SOT and MCT have been completed, results are interpreted to determine if a vestibular abnormality exists. To truly analyze CDP results, response patterns of both the SOT and MCT should be analyzed (Gans & Yellin, 2007). For example, prolonged latencies when measuring a patient's ability to adapt to rapid forward-and-back translations during the MCT are indicative of extravestibular central nervous system lesions (Voorhees, 1989). Additionally, responses from the MCT can also provide insight into a patient's ability to perform daily balance tasks and can be used in the development of vestibular rehabilitation programs (Horak, Shumway-Cook, Crowe, & Black, 1988). For the SOT, many of the subtests can be compared to one another to determine where exactly the deficit is occurring. For example, if the patient performs poorly on conditions 5 and 6, condition 5 only, or condition 6 only, this suggests peripheral vestibular deficits because visual and somatosensory input is in accurate in those conditions. Therefore, the patient has to rely solely on vestibular information to maintain his or her balance (Dickins, Cyr, Graham, Winston, & Sanford, 1992). Results of the SOT can also identify patients who are faking or exaggerating their true vestibular ability. If a patient performed better than or equally as well on conditions 4, 5, and 6 as on conditions 1, 2, and 3, this is indicative of a patient who is providing inaccurate responses as these responses are physiologically impossible (Nasher & Peters, 1990). As evidenced, CDP testing provides unique information that can be used to confirm or support the results of other vestibular tests. While there are some drawbacks to utilizing this type of testing, such as size and cost of the equipment, CDP testing, when accessible, can be a very useful tool for evaluating vestibular function.

Aging and the vestibular system

Developing tests that can accurately assess the aging vestibular system is extremely important as there is a considerable amount of research that focuses on the relationship between age and a decline in vestibular function. One current topic of interest regarding the elderly population and the vestibular system is the high number of falls that occur in this population every year. These falls have been associated with dizziness, balance disorders, and vestibular dysfunction (Agrawal et al., 2009; Alrwaily & Whitney, 2011). Many studies have attempted to identify the specific anatomic changes that occur in the vestibular system during the aging process. In fact, significant cell and neuronal loss with increasing age has been documented in numerous vestibular structures, such as the saccule, utricle, cristae ampullares of the vestibular periphery, primary afferent neurons, and Scarpa's ganglia (Ishiyama, 2009; Park, Tang, Lopez, &

Ishiyama, 2001; Rosenhall, 1973). Initial research from Schuknecht (1964) and Reske-Nielsen and Hansen (1964) found normal vestibular hair cell populations in an older adult cohort. However, the results of these studies may have been limited by the test population and by the tools available during that time for vestibular research. As time progressed, the number of studies in this research area increased and these studies were better able to evaluate the effects of age on vestibular function. For example, Bergstrom (1973) counted nerve fibers associated with different branches of the vestibular nerve in different age groups of men and found a reduction in the number of nerve fibers of up to 37% in the oldest population. Research from Rosenhall (1973) supported this conclusion and reported as much as 20% of a reduction in the hair cell populations of the maculae with increasing age. Additionally, Johnsson (1971) reported saccular degeneration in an older population along with a moderate nerve degeneration in utricular maculae. From these results, researchers were able to identify the connection between BPPV and a decrease in otolithic crystals. Lim (1984) proposed that the association between BPPV and aging resulted from pathology of otoconia. With increasing age, the otoconia are reduced in density and as a result, older adults are more likely to be predisposed to BPPV (Ishiyama, 2009).

In addition to the aforementioned physiologic changes, there is also research to support the relationship between balance and gait disorders and changes in cerebral white matter. According to Guttmann et al. (2000), decreased white matter volume appears to be age-related and plays a role in the mobility impairments seen in the older adult population. Research from Whitman, Tang, Lin, and Baloh (2001) and Baezner et al. (2008) also found associations between degeneration of cerebral white matter and gait and balance dysfunction. Baezner et al. (2008) utilized a large sample size of 639 non-disabled older adults ranging in age from 65-84 years and found a strong association between the severity of age-related white matter changes and the severity of gait and motor compromise. Similarly, research from Whitman et al. (2001), found a more modest relationship between gait and balance dysfunction and cerebral white matter disease. It is evident that the aging process plays a role in the anatomic changes seen in older adults' vestibular structures.

While it is clear that the aging process plays a role in the degeneration of both the vestibular periphery and central nervous system, one area where there is a significant amount of contrasting research is how this degeneration affects results of standard vestibular tests. One vestibular test that has conflicting reports is caloric testing. As previously mentioned, bithermal caloric testing is one of the more important components of the VNG test battery. While some research documents age-related changes on caloric performance, other studies report that caloric response does not decline with age. Early research showed that caloric responses increased in intensity up to the age of 40 years, and then progressively decreased with increasing age (Mulch & Petermann, 1979; Van der Laan & Oosterveld, 1974). Additionally, Maes et al. (2010) found subtle age-related changes on caloric tests, more prominently during warm irrigations. Conversely, Mallinson and Longridge (2004) proposed that caloric responses do not reflect anatomically documented age related senescence of the vestibular system. Furthermore, they suggested that there is no great parallel between caloric testing and imbalance in the elderly. Another recent study from Zapala, Olsholt, and Lundy (2008) also revealed no consistent trend with age in any of the caloric response parameters. It is important to note that while caloric testing is a useful test, it may not be a true reflection of age-related vestibular degeneration because it really only evaluates the integrity of the horizontal semicircular canal. Based on this conflicting research, one could infer that while caloric testing is currently the gold standard of vestibular testing, it may not be as sensitive to identifying the age-related changes in vestibular function as previously thought.

Similar to caloric research, studies on rotational chair tests also yield differing opinions on whether age-related changes in vestibular function can be demonstrated. Maes et al. (2010) found no significant age trends for any response parameter for both the SHA test and the VST. Contrastingly, decreased gain values with advanced age have been reported for SHA testing in the lower frequencies (Wall, Black, & Hunt, 1974), in the higher frequencies (Li et al., 1991) and at higher velocities (Paige, 1991). Interestingly, although Wall et al. (1974) were able to demonstrate age-related changes for the parameter of gain during SHA testing, they were not able to demonstrate any age-related changes for the parameter of phase. For VST, DiZio and Lackner (1990) showed shorter time constants for younger subjects than older subjects, while Furman and Redfern (2001) found no age-related trends for that same parameter. Additionally, it should be noted that most of the previously described age-related trends were relatively small. Obviously, research on age-related changes with respect to rotational chair tests produces variable results. Therefore, it is reasonable to surmise that rotational chair testing is also limited in its ability to detect age-related changes in vestibular function. As a result, there seems to be a need for a test that can more readily identify these changes within the vestibular system.

VEMP testing also produces varying reports on age-related trends. For example, there are many studies that have documented a decrease in the amplitude of the VEMP response with advanced age (Ochi & Ohashi, 2003; Welgampola & Colebatch, 2001; Zapala & Brey, 2004). While there appears to be a consensus on the parameter of amplitude with respect to VEMP responses, there appear to be some contrasting reports on the parameter of latency. Basta, Todt, and Ernst (2005) were unable to demonstrate age-related latency differences, while Welgampola and Colebatch (2001) demonstrated significant prolonged N1 latency values with increasing age. Zapala and Brey (2004) also reported increased P1 and N1 latencies in older adult subjects. Additionally Maes et al. (2010) found age-related effects on the following VEMP response parameters: amplitude, threshold, and latency. They found decreased amplitudes, increased thresholds, and decreased N1 latencies with advanced age. However, there is an important caveat to utilizing VEMP testing to evaluate age-related changes in the vestibular system. One issue that complicates the evaluation of VEMP responses for age-related changes is that the VEMP is assessed through muscle contractions, and with increasing age there is a decrease in muscular function (Hagberg et al., 1989; Meredith et al., 1989; Tomonaga, 1977). Therefore, it is difficult to account for this variable when determining whether VEMP responses are influenced by age-related changes. It is evident, due to the contrasting perspectives on current standard vestibular tests, that no test will perfectly identify vestibular dysfunction and how this dysfunction affects balance in older adults. Development of a more sensitive and specific vestibular test for elderly patents is necessary.

Psychophysics

Psychophysics is a branch of science that studies the relationship between the psychological (subjective or perceptual) and physical aspects of a stimulus (Yost, 2000). Historically, the methods of psychophysics were developed through two approaches. The first approach focused on discrimination. Through discrimination tasks, experimenters were able to obtain an estimate of the smallest difference in a stimulus parameter to which the auditory system is sensitive. Thus, experimenters were interested in the subject's sensitivity to the stimulus change, rather than his or her ability to respond to the experimental situation, such is the case with response proclivity or response bias. Ultimately, discrimination tasks are designed to obtain a measurement of sensitivity and to reduce the effects of response bias.

The second general class of psychophysical procedures are called scaling procedures (Yost, 2000). Scaling procedures are typically focused on obtaining information about various subjective or psychological aspects. Specifically, scaling techniques go beyond measuring whether a subject can detect an auditory stimulus or discriminate between two auditory stimuli, and focus on how the magnitude of a psychological percept changes as a physical parameter changes (Allen, 2007). Magnitude estimation, ratio comparison, and cross-modality matching are three scaling techniques that require a subject to judge the magnitude of a subjective attribute, such as loudness or timbre (Yost, 2000). From these techniques, experimenters are able to develop a scale that relates the perceived magnitude, for example, loudness, to a physical stimulus value, such as level in decibels. Similar to the aforementioned psychophysical approach of discrimination, developing a scale must be done cautiously as there are many potential sources of bias (Pradhan & Hoffman, 1963). One way to reduce biases associated with scaling procedures is to use matching tasks. If loudness scales are developed by matching similar stimuli, such as pure tones that vary slightly in frequency, the effects of bias will be much smaller (Allen, 2007).

The principles of psychophysics are considered the basis of modern day audiologic practice. For example, current audiologic techniques for obtaining a person's auditory detection and discrimination thresholds stem from historic psychophysical methods. Method of limits, method of adjustment, and method of constant stimuli are all examples of psychophysical methods that can be utilized to collect detection and discrimination data. Each method has its own set of advantages and disadvantages; however each one shares a common denominator of having helped shape the practice of modern day audiology. These methods will be described in more detail below.

In the method of limits, the experimenter presents auditory stimuli in either ascending order, which involves increasing the intensity, or descending order, which involves decreasing the intensity (Levitt, 1971; Nachmias & Steinman, 1965). The listener is simply asked to respond with yes or no, depending on whether he or she heard the stimulus. To ensure efficiency during this sequence, the low and upper stimulus values are determined prior to testing (Allen, 2007). This allows stimulus values both above and below threshold levels to be measured. To determine threshold level, the experimenter averages the stimulus values associated with changes in the listener's responses, from detecting a signal to being unable to detect a signal, in both the ascending and descending series. One advantage of this method is that a full range of performance values are able to be obtained. However, as evidenced by the method of limits protocol, one large disadvantage of this procedure is that it can be inefficient if the sole information of interest is threshold determination. Because of this, many variations of the method of limits procedure have been developed, and it is from these variations that today's pure tone thresholds for audiologic evaluations are obtained. One common variation is a staircase procedure, which involves an algorithm that is used to select stimulus values for each trial based on the listener's responses on preceding trial or trials. For example, in a one-down, one-up procedure, the stimulus value is decreased every time the listener correctly responds to the stimulus and is increased every time the listener incorrectly responds or fails to respond to the stimulus. This results in a threshold value that corresponds to 50% correct performance. This variation of the method of limits procedure has helped professionals in the field of audiology obtain thresholds in a more efficient fashion as it places nearly all trials near the level of threshold, rather than including values that deviate significantly, in either direction, from threshold.

The method of adjustment is a variation of the method of limits and places more responsibility on the listener rather than the experimenter. For this procedure, the listener varies the level of the stimulus until it appears equal to or just noticeably different from the reference stimulus (Cornsweet, 1962; Yost, 2000). For example, in the measurement of detection thresholds, the stimulus may gradually increase or decrease, with the direction of change being dictated by the listener. The instructions to the listener are to keep the stimulus at a value that is just barely detectable by responding when he or she does and does not hear the signal (Goldstein, 2010). Therefore, the intensity of the stimulus may gradually increase until the listener denotes, using a response button, that the stimulus was audible. At that point, the intensity of the stimulus gradually decreases until the listener releases the response button indicating that the stimulus is no longer audible. Following this, the stimulus intensity begins to increase once again, and the whole procedure is repeated. In order to determine threshold level, the experimenter must analyze the average change between successive responses. This indicates audible and inaudible signal values and helps to determine the level at which the listener detects the stimulus. While the method of adjustment may sound more efficient than the method of limits, it introduces a new source of bias by placing most of the responsibility on the listener. For this reason, the method of adjustment is usually not the procedure of choice for obtaining threshold levels.

Lastly, the method of constant stimuli differs from the aforementioned procedures because rather than estimating a single threshold value, the experimenter selects a variety of stimulus levels that are both above and below the actual threshold level (Masin & Fanton, 1989; Yost, 2000). In this procedure, several stimuli are presented at each of the many stimulus values and the listener is asked to respond yes when the stimuli are audible and no when the stimuli are inaudible. The performance is calculated for each stimulus value across a block of trials. From this information, a psychometric function may be generated and threshold values can then be extrapolated from these fitted functions (Allen, 2007; Kingdom & Prins, 2010). Similar to the method of limits, the method of constant stimuli can be rather inefficient due to the wide range of stimuli being presented to the listener. However, unlike the method of limits, the method of constant stimuli has the advantage of reducing listener bias due to its ability to randomize the order in which those stimulus values are presented.

Many of today's audiologic practices have been greatly influenced by the development and modification of these methods. In current audiologic practice, the methods for obtaining detection thresholds for pure tone audiometry stem from these psychophysical principles. During pure tone testing, thresholds are obtained, with threshold being defined as the lowest intensity at which a patient is able to respond to a stimulus 50% of the time [American Speech-Language Hearing Association (ASHA), 2005]. The ability to acquire detection thresholds stems from modifications to the aforementioned psychophysical methods. It is from these psychophysical procedures that pure tone audiometry has been developed. In fact, pure tone audiometry has long been a vital component to the audiologic test battery. According to Roeser and Clark (2007), pure tone audiometry is unequivocally the gold standard of every audiological evaluation. Results of pure tone testing can be used to make initial diagnoses of normal versus abnormal hearing sensitivity, including the type and degree of hearing loss when the results are not within normal limits. From this, the audiologist can then determine whether additional audiologic testing needs to be performed or if the patient should be referred to a medical specialist, such as an otolaryngologist (ENT). Additionally, based on the results of pure tone testing, audiologists can recommend treatment intervention, such as that of a hearing aid, assistive listening device, or cochlear implant.

Psychophysical methods have tremendously helped the field of audiology to develop clinical tools that accurately and efficiently evaluate auditory function. Given that the auditory and vestibular systems are so closely related, one might infer that psychophysical methods should also be used to evaluate vestibular function. However, at this time, it is not common practice to use psychophysical procedures to evaluate the vestibular system. One reason these methods have not been utilized is because vestibular functions are most commonly assessed by observation of the visual system/eye movements. Nystagmus is an easy phenomenon for a clinician to observe, particularly spontaneous nystagmus. For this reason, evaluating the vestibular system through psychophysical methods has not been necessary. Conversely, psychophysical methods were necessary to the evaluation of auditory function because historically, auditory reflexes were not as accessible or easy to observe as vestibular reflexes. Prior to the development of auditory evoked responses, the only method for evaluating a person's hearing status was to obtain detection and discrimination thresholds using psychophysical techniques. While audiology has continued to evolve and produce more sophisticated methods for the evaluation of hearing, pure tone testing still remains common practice and is essential to the audiologic test battery. Another reason psychophysical procedures are not common for evaluating vestibular function is that these methods can be very time consuming. Prior to modifications and adaptive procedures, psychophysical methods for audiology were inefficient and required a lengthy time commitment. It was only after modifications that evaluation of the auditory system with these measures was practical and efficient. Therefore, as other vestibular tests were able to better evaluate vestibular function in a more practical and efficient manner, psychophysical methods were not employed. Lastly, because the vestibular system is easily modeled as a second-order differential equation, there was never any necessity to utilize psychophysical procedures. A differential equation is one where the value of a function is related to a differential of that function. Essentially, models of the semicircular canals and the fluid inside of the canals act according to a differential equation. Because we measure the function of the horizontal semicircular canal by observing eye movements, these too, follow the concept of a differential equation. Therefore, by seeing how the eye movements relate to the speed of the rotational chair, a calculation can be performed in order to determine the differential equation related to the eye movements. The values of that differential equation have normal standards for most people, and thus, if the performance value falls outside the range of normal, the individual may have vestibular dysfunction. Ultimately, by having the ability to simply perform a calculation that easily models the effects of a rotational chair test, it is easy to see why psychophysical testing has not been used for present day vestibular evaluations.

With advancing age, anatomic degradation occurs in the vestibular structures. It is also clear from the various research studies, that the majority of current standard tests of balance are not sensitive enough to reflect these age-related changes in vestibular function. This is one reason why using psychophysical methods to evaluate the vestibular system might be useful. It is possible that psychophysical testing may be more sensitive to vestibular dysfunction, particularly dysfunction found in older adults, than current vestibular tests. Additionally, psychophysical testing may yield new information that has not been previously documented with other vestibular tests. This information might help therapists and audiologists to better create and design vestibular rehabilitation programs. Another reason it might be beneficial to use psychophysical testing is because it has been successfully used to evaluate function of the auditory system. The auditory system and vestibular system are so closely related and if a certain type of test is able to efficiently and accurately evaluate the auditory system, one can infer that the same type of test may have the same success with the vestibular system.

Study Objective

Psychophysical testing may provide additional or alternate information compared to current standard clinical tests of balance, particularly in the elderly population. The present study had two goals: to determine if older subjects have poorer vestibular psychophysical thresholds than younger subjects, and to determine if psychophysical thresholds correlate with performance on standard tests of vestibular function.

CHAPTER 2

METHODS

Subjects

This study was approved by the Washington University School of Medicine Human Studies Committee. Eighteen older adults between the ages of 63 – 84 years (mean = 71 years, standard deviation = 6.7 years) and thirteen younger adults between the ages of 20 – 25 years (mean = 22, standard deviation = 1.4 years) participated in the present study. The older adults were recruited from Washington University's Psychology Department older adult volunteer pool, while the younger adults were recruited from the Washington University community. All subjects participated in the psychophysical testing portion of the experiment, however only the older adult cohort participated in the standard rotational chair testing, which included sinusoidal harmonic oscillation and steps of velocity. One older adult and three younger adult participants were unable to complete the discrimination portion of the psychophysical experiment due to time constraints, and therefore, these results are documented with an n of 17 and an n of 10, respectively. There was no history of otologic disease, neurologic disease, or a history of falling among any of the participants. Pure tone average (500, 1000, and 2000 Hz) auditory thresholds of older adult subjects were better than 50 dB HL. No subject reported being aware of motor noise from the custom-designed rotational chair or other possible motion cues.

Psychophysical Testing

The experimental apparatus consisted of a customized race car seat rotated about the earth-vertical axis by an electric motor (Kollmorgen Goldstar DDR D063M7, Danaher Motion, Radford, VA). Subjects were held in the chair using a four-point harness and were surrounded by foam padding to reduce proprioceptive feedback. Additionally, all subjects wore a blindfold to reduce the possibility of visual cues. Gaussian noise generated by Matlab (MathWorks, Natick, MA) was provided by headphones to prevent perception of external noise, such as motor noise (FM Basic 26000, MSA Sordin, Värnamo, Sweden or MDR-7506, Sony, Japan). Chair motion was generated by custom-written software in Matlab and sent to the chair controller via the Matlab Data Acquisition Toolbox in conjunction with a National Instruments Data Acquisition device (BNC2090, Austin, TX). Details of this method have been published previously, including control experiments to verify that sensory cues were limited to vestibular input only (Mallery, Olomu, Uchanski, Militchin, & Hullar, 2010).

Two separate psychophysical experiments were performed as part of this study. Each experiment utilized a two-alternative, two-interval forced-choice paradigm. In this paradigm, the subject is tested using multiple trials, each consisting of a pair of sequential stimulus intervals termed the “reference” and the “comparison” intervals (Green & Swets, 1966; Macmillan & Creelman, 2005). The “reference” stimulus usually has a constant amplitude, whereas the amplitude of the “comparison” stimulus varies among trials. In this experimental design, one can measure the threshold as well as the minimum difference in amplitude that is required for a subject to discriminate between two stimuli. For special instances when the amplitude of the reference is zero, this value is labeled as the detection threshold.

The threshold is defined as the difference between the reference and comparison amplitudes at which subjects correctly identify the comparison interval with a certain accuracy. One way to determine a threshold is to use an “adaptive staircase” model in which the comparison stimulus starts well above the reference stimulus and is reduced until the subject correctly identifies the comparison interval a certain percentage of the time. For the present study, a “three-down one-up” paradigm was utilized. In this paradigm, when a subject correctly identifies the comparison interval three times in a row, the next trial is made more difficult by decreasing the comparison stimulus amplitude to a level closer to the reference amplitude. Conversely, each time a subject does not respond correctly, the comparison stimulus amplitude is increased to make the next trial easier. Ultimately through this paradigm, a value is reached at which the amplitude of the comparison stimulus is relatively stable across trials (Leek 2001). The mathematics of the three-down one-up design ensures that this point of stability is the threshold where the subject is correct 79% of the time (Leek 2001).

The first psychophysical experiment included obtaining detection thresholds for all subjects. In the detection experiment, the reference velocity of the customized rotational chair was zero and the initial comparison velocity was 5 deg/sec. The second psychophysical experiment involved acquiring discrimination thresholds for all subjects. For the discrimination experiment, the reference velocity was 60 deg/sec and the initial comparison velocity was 75 deg/sec. The order of the two intervals was randomized for both psychophysical experiments and subjects were instructed to identify which interval was “faster” by responding with “one” or “two”. The trajectories of these two paradigms are shown in Figure 1.

Standard Tests of Vestibular Function

All older adult subjects also underwent standard tests of vestibular function, including sinusoidal harmonic oscillation and steps of velocity rotational chair testing (System 2000, Micromedical Technologies, Chatham, IL). Subjects were seated in a rotational chair in a completely darkened enclosure. A safety belt was utilized to ensure that subjects were securely strapped to the chair. Additionally, subjects’ heads were stabilized in a head rest to ensure a head-upright position. Subjects were fit with infrared goggles, which allowed the tester to monitor eye movements from outside the test enclosure. A speaker was also located in the enclosure to ensure that subjects were in a two-way communication with the tester. Rotations were performed with the subjects’ eyes open while performing mental alert tasks throughout the duration of the testing. A standard calibration of horizontal eye movements was performed prior to each testing session.

First, all older adult participants were subjected to sinusoidal harmonic oscillation testing. Each subject underwent testing at four different frequencies: 0.025, 0.05, 0.25, and 0.5 Hz. Assessing multiple frequencies during sinusoidal harmonic oscillation testing is analogous to testing multiple frequencies during a hearing test, and provides a more complete picture of an individual’s vestibular function. During each frequency, subjects were instructed to keep their eyes open and

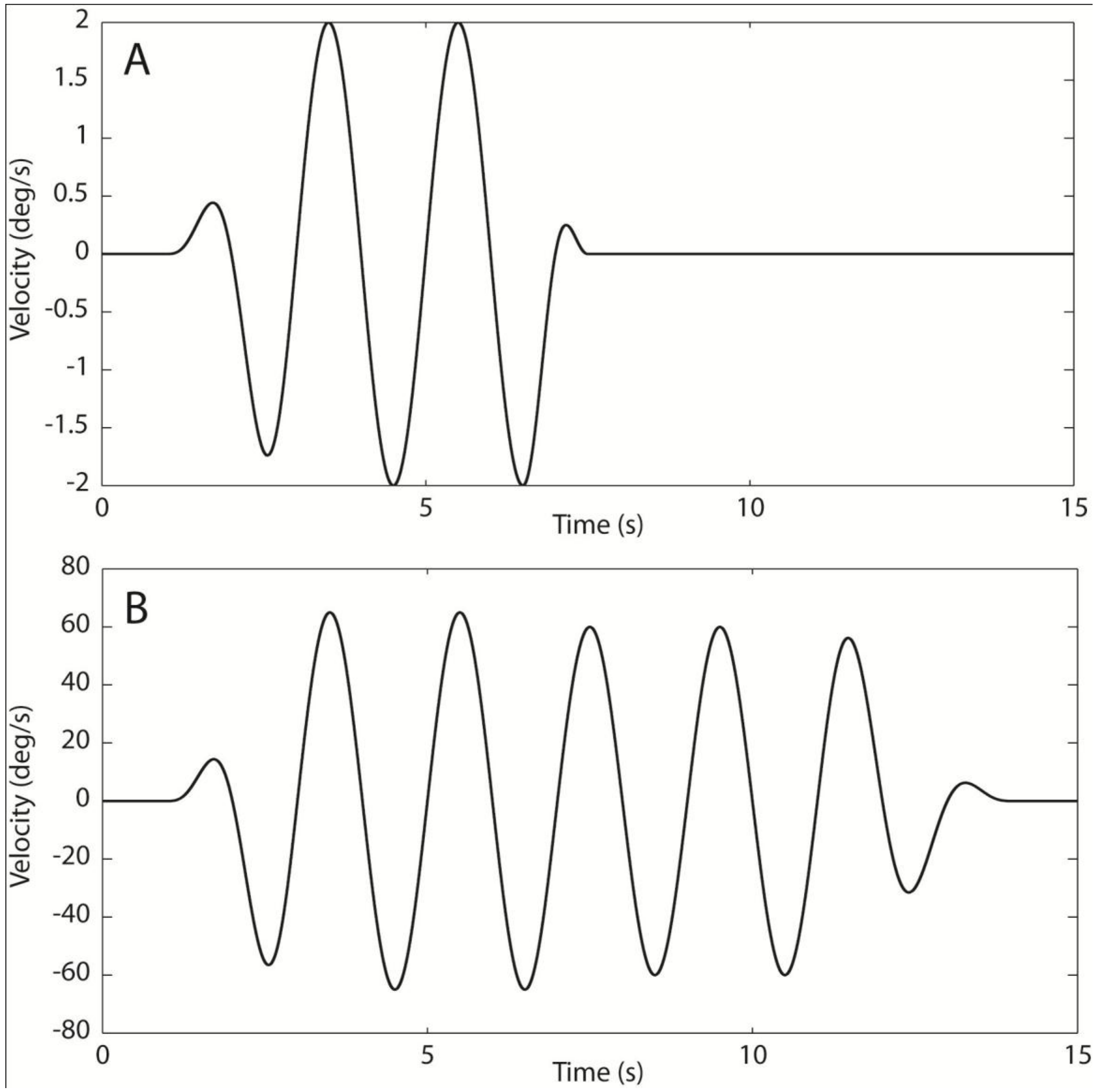

Figure 1. Stimulus trajectories. Positive numbers demonstrate clockwise chair rotation. Panel A: Detection paradigm. In this example, the comparison interval, with a peak velocity of 2 deg/sec, occurs prior to the reference interval. The reference interval has a peak velocity of 0 deg/sec (stationary). Panel B: Discrimination paradigm. In this example, the comparison interval has a velocity of 65 deg/sec and also occurs prior to the reference interval. The reference interval in this example has a peak velocity of 60 deg/sec.

perform mental alert tasks. Once data were obtained for each frequency, an analysis of the measurements of gain, asymmetry, and phase were performed. Gain measures the amplitude of nystagmus in response to head movement and depends on the velocity of rotation (Hirsch, 1986). Symmetry evaluates and compares clockwise and counterclockwise nystagmus. And, phase measures the temporal relationship between the initiation of changes in head, or chair, movement velocity and changes in eye movement velocity (Gans & Yellin, 2007).

Following sinusoidal harmonic oscillation testing, older adult subjects performed VST. VST is used to measure the decay rate of nystagmus following an abrupt angular acceleration, or deceleration, to the right or left in the rotational chair (Brey et al., 2008). For the present experiment, this test was performed at 0.5 Hz in both the clockwise direction and counterclockwise direction. Subjects were instructed to keep their eyes open and perform mental alert tasks throughout the duration of testing, even following the abrupt deceleration of the rotational chair. Similar to the sinusoidal harmonic oscillation testing, the components of gain, phase, and asymmetry were analyzed to determine normal versus abnormal vestibular function.

Testing Sessions

Each subject was given the option to complete all testing in one day or to divide the testing into two separate sessions. Subjects were encouraged to take breaks in between detection and discrimination experiments. The total test time was approximately one hour for younger adult subjects and approximately three hours for older adult subjects.

Data Analysis

The compiled psychophysical threshold data was analyzed for statistical differences using the Mann-Whitney U test. Additionally, Spearman's Rank Order correlation was utilized to determine correlations between psychophysical data and standard rotational chair measurements, such as VOR gain and phase.

CHAPTER 3

RESULTS

Psychophysical detection thresholds as a function of age

A scatterplot of vestibular detection thresholds for both younger and older subjects is shown in Figure 2. The mean detection threshold (± SD) of the younger population was 0.73 ± 0.32 deg/sec, while the mean detection threshold for the older cohort was 1.09 ± 1.13 deg/sec. While the detection results for the younger population are tightly grouped, the older population demonstrates more variability in thresholds, including two noticeable outliers. However, there was no statistical difference between the thresholds of the two groups (Mann-Whitney, $p = 0.575$).

Psychophysical discrimination thresholds as a function of age

A scatterplot of vestibular discrimination thresholds for both the younger and older populations is shown in Figure 3. The mean discrimination threshold (± SD) of the younger population was 4.8 ± 1.87 deg/sec and of the older population was 5.99 ± 2.27 deg/sec. These results demonstrate more variability than the reported detection thresholds for both populations. Additionally, there are three clear outliers for the older adult population. Of the three discrimination threshold outliers and two detection threshold outliers identified among older subjects, only one represents the same participant for the two data sets. Lastly, there was no statistical difference between thresholds of the two groups (Mann-Whitney, $p = 0.280$).

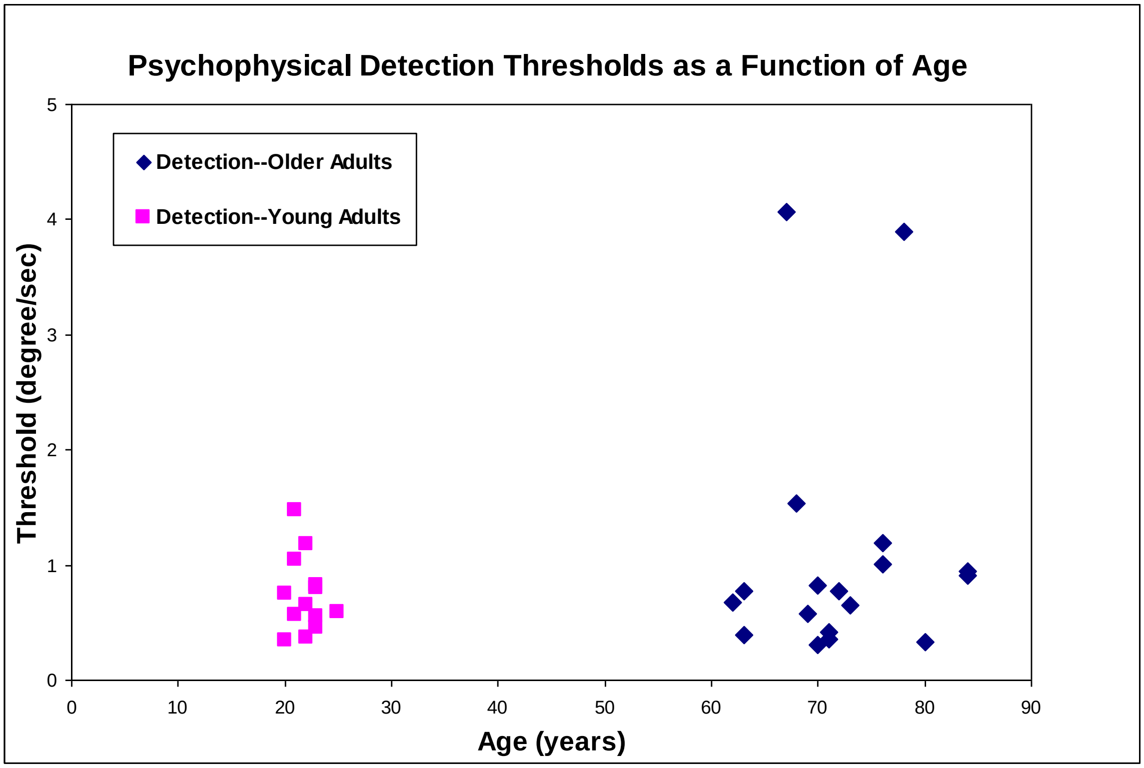

Figure 2. Detection thresholds as a function of age. Diamonds represent older subjects and squares represent younger subjects.

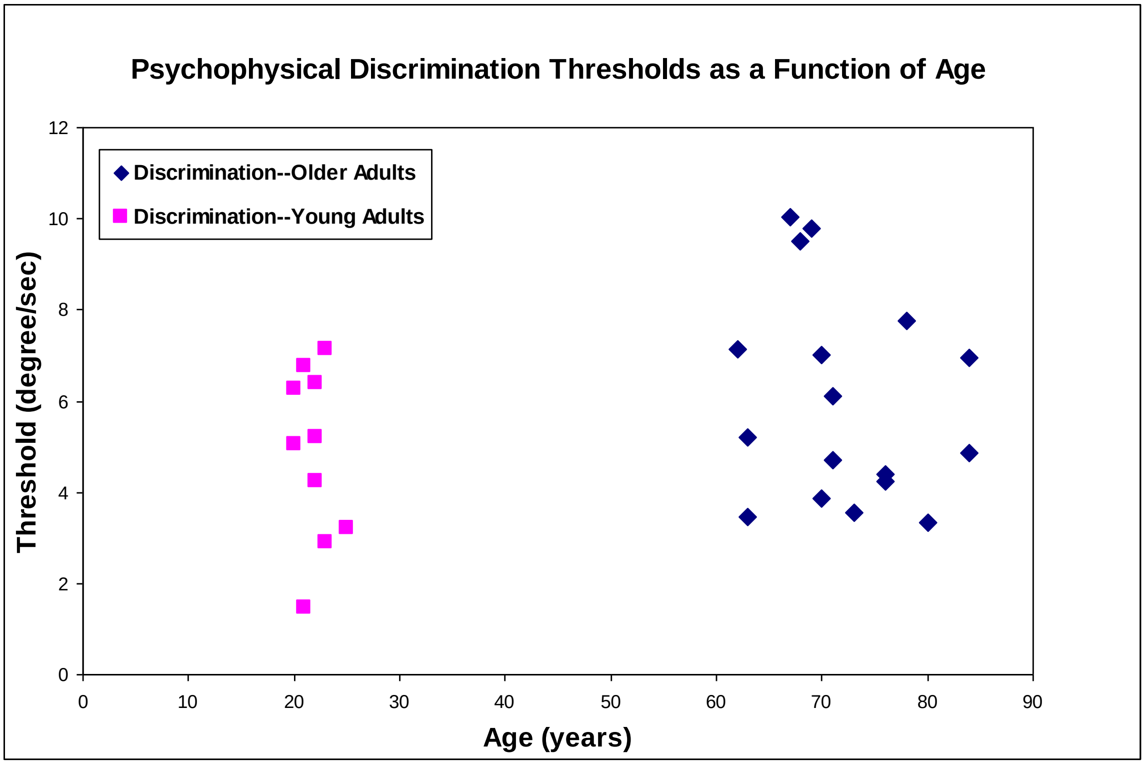

Figure 3. Discrimination thresholds as a function of age. Diamonds represent older subjects and squares represent younger subjects.

Psychophysical thresholds as a function of gain

Scatterplots of psychophysical thresholds as a function of VOR gain at 0.025 Hz and 0.5 Hz for older adult subjects are shown in Figures 4 and 5, respectively. Gain represents the velocity of eye movement divided by the velocity of head movement. Therefore, a score of 1 is a perfect response and 0 is no response to rotational stimulation. Essentially, all older adult subjects had normal results as established by the normative data for gain at 0.025 Hz. (Micromedical Technologies, 2004). Additionally, no correlation was found between gain at 0.025 Hz and psychophysical thresholds for detection (Spearman's Rank Order, r= .336, p= .182) or discrimination (Spearman's Rank Order, r= .083, p= .744). There was, however, a mild correlation found between gain at 0.5 Hz and psychophysical thresholds for detection (Spearman's Rank Order, r= .559, p= .019). Lastly, no correlation was found between gain at 0.5 Hz and psychophysical thresholds for discrimination (Spearman's Rank Order, r= .337, p= .179).

Psychophysical thresholds as a function of phase

Scatterplots of psychophysical thresholds as a function of rotational chair phase lead at 0.025 Hz and 0.5 Hz for older adult subjects are shown in Figures 6 and 7, respectively. Phase lead is the value to which compensatory eye movements lead the movement of the head. No correlation was found between phase lead at 0.025 Hz and psychophysical thresholds for detection (Spearman's Rank Order, r= -.269, p= .288) or discrimination (Spearman's Rank Order, r= -.116, p= .652). Additionally, no correlation was found between phase lead values at 0.5 Hz and psychophysical thresholds for detection (Spearman's Rank Order, r= -.106, p= .680) or discrimination (Spearman's Rank Order, r= -.045, p= .854).

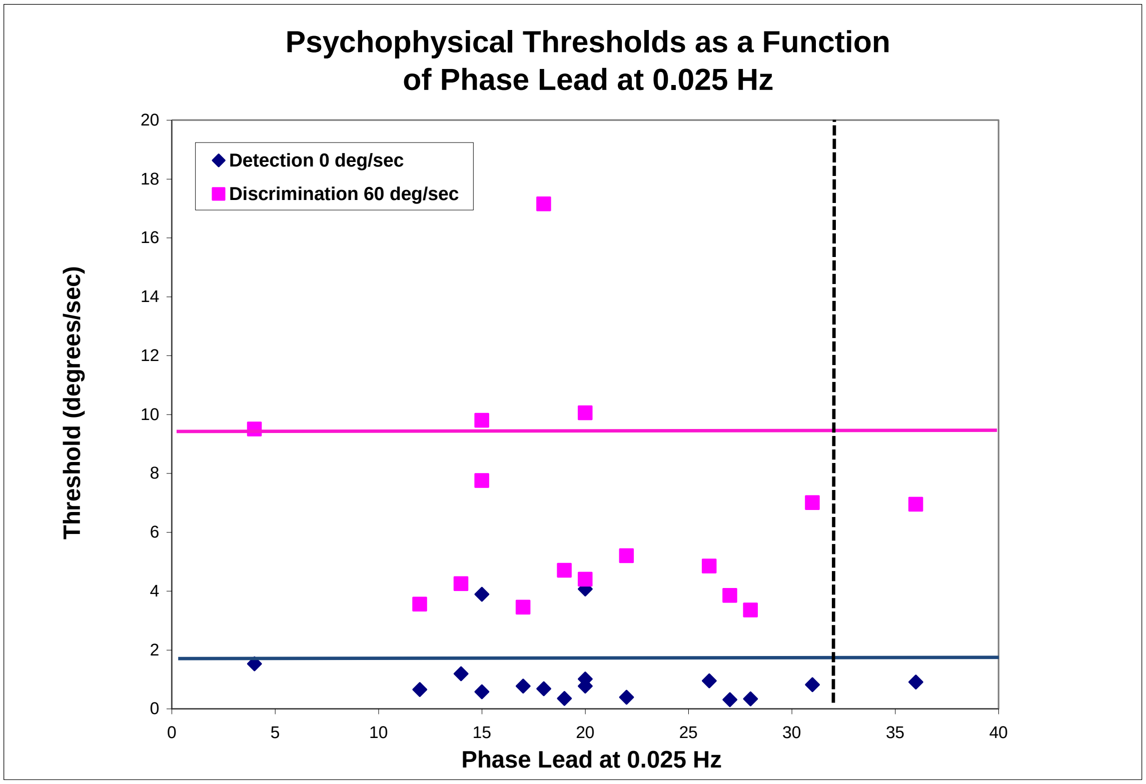

Figure 4. Psychophysical thresholds as a function of rotational chair gain at 0.025 Hz for older adult subjects. The solid blue line represents the upper limit for normal detection thresholds (1.40 deg/s) and the solid pink line represents the upper limit for normal discrimination thresholds (9.62 deg/s). Data points above these lines demonstrate abnormal thresholds. The dotted black line represents the lower limit for normal gain (0.39) and data points to the right of this line demonstrate normal gain.

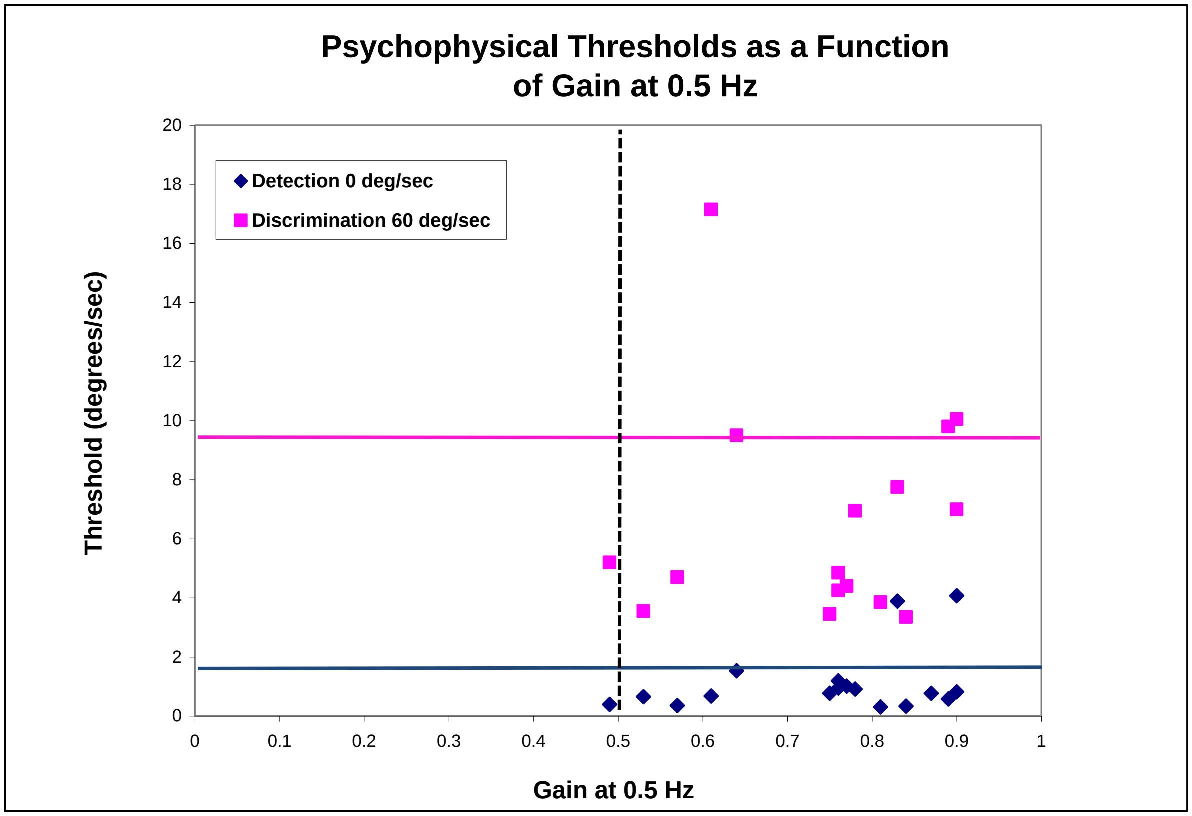

Figure 5. Psychophysical thresholds as a function of rotational chair gain at 0.5 Hz for older adult subjects. The solid blue line represents the upper limit for normal detection thresholds (1.40 deg/s) and the solid pink line represents the upper limit for normal discrimination thresholds (9.62 deg/s). Data points above these lines demonstrate abnormal thresholds. The dotted black line represents the lower limit for normal gain (0.5) and data points to the right of this line demonstrate normal gain.

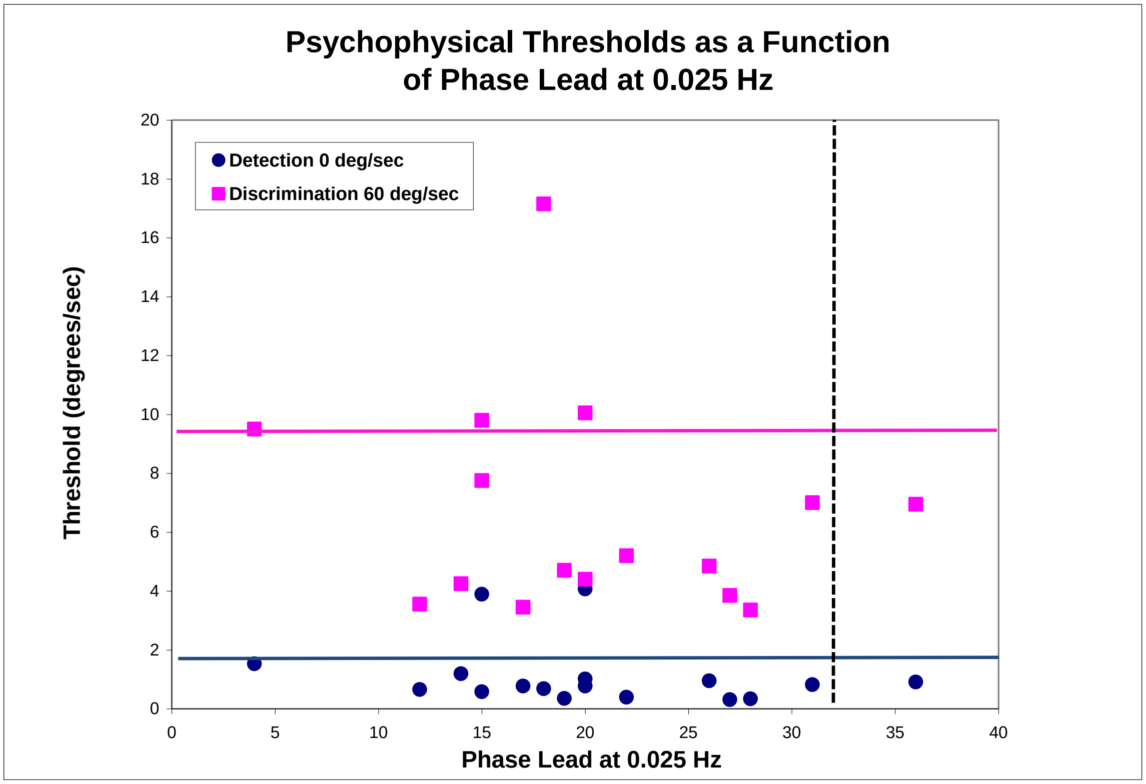

Figure 6. Psychophysical thresholds as a function of rotational chair phase lead at 0.025 Hz for older adult subjects. The solid blue line represents the upper limit for normal detection thresholds (1.40 deg/s) and the solid pink line represents the upper limit for normal discrimination thresholds (9.62 deg/s). Data points above these lines demonstrate abnormal thresholds. The dotted black line represents the upper limit for normal phase lead (32 deg) and data points to the right of this line demonstrate abnormal phase lead.

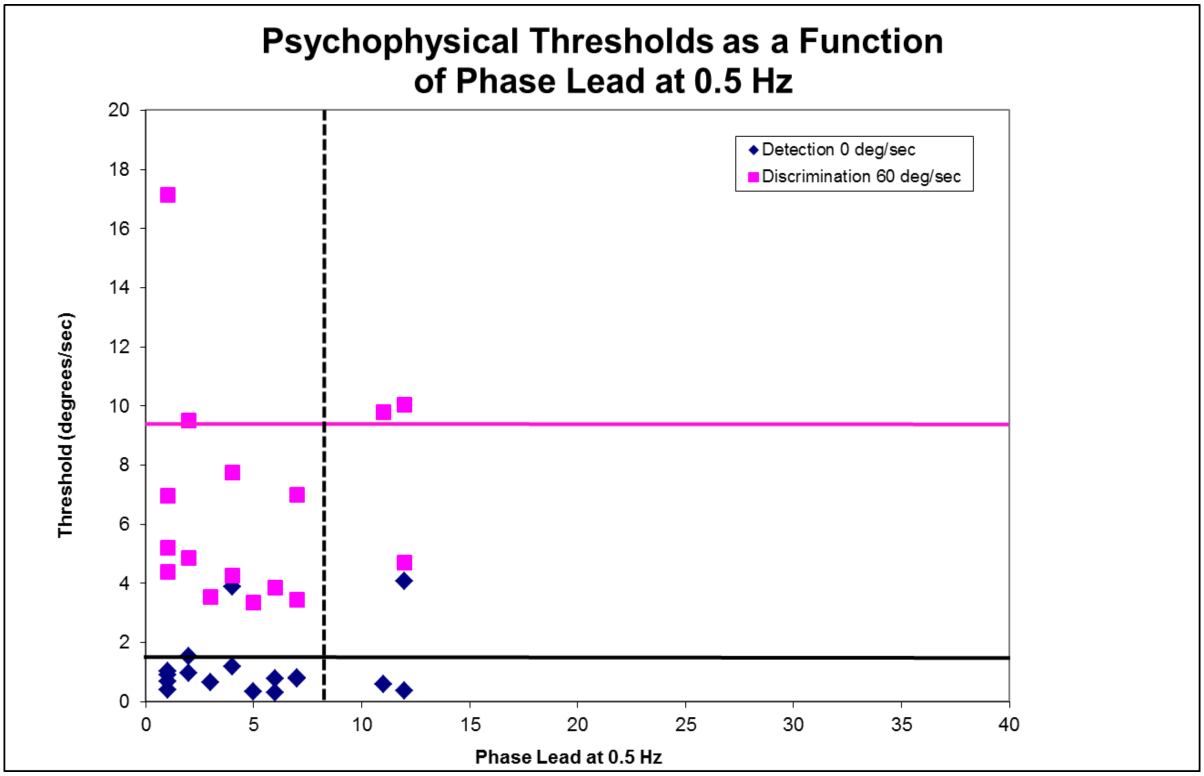

Figure 7. Psychophysical thresholds as a function of rotational chair phase lead at 0.5 Hz for older adult subjects. The solid blue line represents the upper limit for normal detection thresholds (1.40 deg/s) and the solid pink line represents the upper limit for normal discrimination thresholds (9.62 deg/s). Data points above these lines demonstrate abnormal thresholds. The dotted black line represents the upper limit for normal phase (8 deg) and data points to the right of this line demonstrate abnormal phase lead values.

CHAPTER 4

DISCUSSION

Vestibular loss: Variable, not inevitable

The data indicate that generally, with the exception of a few elderly outliers, older adults perform similarly to younger adults on psychophysical detection and discrimination tasks. These results suggest that vestibular dysfunction is not inevitable; that while some older adults demonstrate vestibular abnormalities, others are able to maintain relatively "normal" thresholds on psychophysical detection and discrimination tasks. These results were not anticipated based on previous research from Baloh, Enrietto, Jacobson, and Lin (2001), who reported age-related changes in vestibular performance on VOR responses. One reason for the contrasting results may be due to variability within the aging process itself. As evidenced by the present data, the older adult population demonstrated greater variability on detection and discrimination tasks than their younger adult cohort. These results suggest that the aging process is a unique process, and one that affects each person individually. In fact, this variability is also exhibited in hearing research when older adults demonstrate variable responses to high-frequency tonal stimuli (Pearson et al., 1995). Regardless of the variability in the natural aging process, the present data suggest that specific causes of vestibular loss in the older adult population may one day be identifiable, and eventually, treatable.

Psychophysical thresholds and VOR

The data presented here also suggest that there is no relationship between VOR measurements of gain and phase and psychophysical thresholds. Although a mild correlation was found between VOR gain measurements at 0.5 Hz and psychophysical thresholds for detection, it is evident that abnormal values on standard rotational chair tests do not guarantee abnormal thresholds on psychophysical tasks. Because the test results did not correlate, this indicates that psychophysical testing may provide information not afforded by previous standard rotational chair tests. For example, as demonstrated in the present data, the normal range of detection thresholds and discrimination thresholds at 0.5 Hz for younger subjects and the majority of older adult subjects were less than 2 deg/sec and less than 7 deg/sec, respectively. These data ranges are much smaller than previously reported ranges of normal values for maximal eye speed during VOR-driven eye movements. During standard clinical testing of earth vertical rotations at 0.2 Hz, the range of normal eye speed is more than 36 deg/sec (Baloh, Honrubia, Yee, & Hess, 1984). Additionally, the frequency of 0.4 Hz elicits eye speeds of more than 18 deg/sec. These differences suggest that the psychophysical thresholds utilized in the present study may represent a more accurate test with increased sensitivity and specificity for vestibular dysfunction than conventional rotational chair testing.

Differences between detection and discrimination

As previously mentioned, of the three discrimination threshold outliers and two detection threshold outliers identified among older subjects, only one represents the same participant for the two data sets. The remaining two discrimination threshold outliers and one detection threshold outlier represented three different individuals from the older adult population. These results imply that the two thresholds may measure similar, but not identical peripheral involvement to central vestibular function, and thus may offer complementary information. This notion could be supported by current documentation on the workings of the vestibular periphery. It has been reported that there are three different afferent nerve fibers that transmit rotational information to the brain (Baird, Desmadryl, Fernandez, & Goldberg, 1988; Hullar, Della Santina, Hirvonen, Lasker, Carey, & Minor, 2005). Each afferent type is likely tuned to particular head motions, as suggested by Beraneck and Straka (2010). As a result, "regular" afferents might indicate slow or low-frequency variations in amplitude, whereas "irregular" afferents might signal fast or high-frequency head motions (Sadeghi, Chacron, Taylor, & Cullen, 2007). This suggested difference among afferent types is proposed to be the cause for different responses to head thrusts and low-frequency rotational chair movements.

Additionally, the majority of psychophysical studies on vestibular function in humans with normal vestibular abilities have focused on detection thresholds (Benson, Hutt, & Brown, 1989; Gianna, Heimbrand, & Gresty, 1996; Grabherr, Nicoucar, Mast, & Merfeld, 2008) although recently there has been more research dedicated to evaluating discrimination thresholds (MacNeilage, Banks, DeAngelis, & Angelaki, 2010; Mallery et al., 2010). The finding in the present study that more information was provided by the addition of discrimination thresholds, in tandem with detection thresholds, has been well-documented in previous studies of auditory function (Erber, 1982; Hudgins, Hawkins, Kaklin, & Stevens, 1947;Thibodeau, 2007). To truly evaluate a person's auditory ability, it is important to not only obtain a person's detection thresholds across a range of frequencies, but also to measure how the person is able to use those thresholds to understand more real-world applicable stimuli, such as a speech stimulus. For example, the short increment sensitivity index (SISI) test measures cochlear damage in sensory hearing losses. While a person may have detection thresholds within the normal hearing range as graphed on an audiogram, if a cochlear pathological condition exists, results on the SISI will be poor as a result of the cochlear pathology (Buus, Florentine, & Redden, 1982a; Buus, Florentine, & Redden, 1982b). In fact, these same principles can be extended to other sensory systems, including the visual system, where a loss of contrast sensitivity is an indicator of glaucoma (Hosking et al., 2001).

Central function

Psychophysical testing can be used to measure peripheral vestibular function, however it may also provide pertinent information about the status of the central vestibular system. Recent studies have demonstrated that psychophysical measures do not correlate well with the VOR, which is thought to be a relatively short reflexive circuit present at the brainstem level (Merfeld, Park, Gianna-Poulin, Black, & Wood, 2005a; Merfeld, Park, Gianna-Poulin, Black, & Wood, 2005b). The VOR depends on processing of vestibular signals in the brainstem and providing an output to motor neurons, which then guide eye movements (Grabherr et al., 2008). Conversely, perceptual responses involve cortical evaluation of vestibular signals, which ultimately makes them different from standard VOR. This adds credibility to the idea that psychophysical measures may provide useful information not obtained through standard rotational chair tests, and also, that these measures may be sensitive enough to evaluate vestibular structures not previously tested.

Limitations of the present study

The present study was a preliminary report of the effect of age on psychophysical vestibular measures of detection and discrimination. One clear limitation of the study was the relatively small number of participants, for both populations, that were included in the data analysis. Also, specific to the older adult population, there was a lack of diversity among the participants. Although, there was a fairly wide age range in this population, the subjects who participated were healthy, independent, and active individuals who were research volunteers from the Washington University community. The current study did not include any person over the age of 84 or any one who lived in an assisted-living environment. This may have attributed to the results that in general, older adults perform similarly on detection and discrimination tasks as younger adults.

Another study limitation was a lack of randomization among the psychophysical tests administered to subjects. Although detection and discrimination thresholds measure two different responses, they are obtained in a similar fashion. That being said, there may have been a learning curve for subjects during psychophysical testing, which may have influenced the test results. The present study attempted to reduce this potential bias by providing patients with a few trial runs prior to each task; however it is still possible that patients felt more comfortable and improved in accuracy as the testing went on.

CHAPTER 5

CONCLUSION

The present study had two objectives: to determine if older adult subjects have poorer vestibular psychophysical thresholds than younger adults, and to ascertain whether psychophysical measures correspond to performance on standard rotational chair tests in the older adult population. Although there were no significant differences in performance on psychophysical thresholds between older and younger adults, this may be the result of the small number of participants included in the study and the relatively healthy older adult population utilized. With regards to the few outliers identified in the older adult population, the significance of these results is unknown. None of the subjects had a history of falling, however, the data collected did not indicate whether these individuals had adjusted their activities to prevent falls or if other sensory systems had been compensating for their vestibular loss. Also, generally speaking, there was no correlation found between the measures of VOR and psychophysical thresholds, with the exception of a mild correlation between VOR gain and detection thresholds at 0.5 Hz. Despite this mild correlation, it is evident that vestibular abnormality on standard rotational chair tests does not indicate abnormality on psychophysical tests, and vice versa. Overall, these results infer that psychophysical testing accesses different information than that obtained on standard rotational chair testing. As previously mentioned, the need is great for more specific and sensitive vestibular tests for evaluating the older adult population, particularly those individuals who are susceptible to falling. With more and more research being conducted in this area, it is promising that psychophysical tests, such as those reported here, may mature into new tools for clinical evaluation and may help to better identify older patients with vestibular loss who are at risk for associated morbidities due to falls.

LIST OF REFERENCES

Agrawal, Y., Carey, J.P., Della Santina, C.C., Schubert, M.C., & Minor, L.B. (2009). Disorders of Balance and Vestibular Function in US Adults: Data From the National Health and Nutrition Exam Survey, 2001-2004. *Archives of Internal Medicine, 169*, 938-944.

Allen, P. (2007). An Introduction to Acoustics and Psychoacoustics. In B. Brandenburg (Ed.), *Audiology Diagnosis* (2nd ed., pp. 169-194). New York: Thieme Medical Publishers.

Alrwaily, M., & Whitney, S.L. (2011). Vestibular Rehabilitation of Older Adults with Dizziness. *Otolaryngologic Clinics of North America, 44 (2)*, 473-496.

American Speech-Language Hearing Association. (2005). Guidelines for Manual Pure-Tone Threshold Audiometry [Guidelines]. Available from www.asha.org/policy

Baezner, H., Blahak, C., Poggesi, A., Pantoni, L., Inzitari, D., Chabriat, H., et al. (2008). Association of gait and balance disorders with age-related white matter changes: The LADIS study. *Neurology, 70(12)*, 935-942.

Baird, R.A., Desmadryl, G., Fernandez, C., & Goldberg, J.M. (1988). The vestibular nerve of the chinchilla. II. Relation between afferent response properties and peripheral innervation patterns in the semicircular canals. *Journal of Neurophysiology, 60(1),* 182-203.

Baloh, R.W., Enrietto, J., Jacobson, K.M., & Lin, A. (2001). Age-related changes in vestibular function: A longitudinal study. *Annals of the New York Academy of Sciences, 942*, 210-219.

Baloh, R.W., & Honrubia, V. (1990). *Clinical Neurophysiology of the Vestibular System* (pp. 112-129). Philadelphia: F A Davis.

Baloh, R.W., Honrubia, V., & Jacobson, K. (1987). Benign positional vertigo: clinical and oculographic features in 240 cases. *Neurology, 37(3)*, 371-378.

Baloh, R.W., Honrubia, V., Yee, R.D., & Hess, K. (1984). Changes in the human vestibulo-ocular reflex after loss of peripheral sensitivity. *Annals of Neurology, 16(2)*, 222-228.

Baloh, R.W., Yee, R.D., Kimm, J., & Honrubia, V. (1981). The vestibulo-ocular reflex in patients with lesions of the vestibulocerebellum. *Experimental Neurology, 72(1)*, 141-152.

Barber, H.O., & Stockwell, C.W. (1980). *Manual of Electronystagmography* (2nd ed.). St. Louis: CV Mosby.

Basta, D., Todt, I., Ernst, A. (2005). Normative data for P1/N1-latencies of vestibular evoked myogenic potentials induced by air- or bone-conducted tone bursts. *Clinical Neurophysiology, 116(9)*, 2216-2219.

Benson, A.J., Hutt, E.C., & Brown, S.F. (1989). Thresholds for the perception of whole body angular movement about a vertical axis. *Aviation, Space, and Environmental Medicine, 60(3)*, 205-213.

Beraneck, M., & Straka, H. (2010). Vestibular signal processing by separate sets of neuronal filters. *Journal of Vestibular Research, 21(1)*, 5-19.

Bergstrom, B. (1973). Morphology of the vestibular nerve. II. The number of myelinated vestibular nerve fibers in man at various ages. *Acta Otolaryngologica*, *76*, 173-179.

Brandt, T. (1993). Background, technique, interpretation, and usefulness of positional and positioning testing. In G.P. Jacobson, C.P. Newman, & J.M. Kartush (Eds.), *Handbook of balance function testing* (pp. 123-155). St. Louis: Mosby-Year Book.

Brantberg, K., Bergenius, J., & Tribukait, A. (1999). Vestibular-evoked myogenic potentials in patients with dehiscence of the superior semicircular canal. *Acta Otolaryngologica, 119(6)*, 633-640.

Brey, R.H., McPherson, J.L., & Lynch, R.M. (2008). Technique, interpretation, and usefulness of whole body rotational testing. In G.P. Jacobson & N.T. Shepard (Eds.), *Balance function assessment and management* (pp.281-317). San Diego: Plural Publishing.

Buus, S., Florentine, M., & Redden, R.B. (1982a). The SISI Test: A review. Part I. *Audiology, 21(4)*, 273-293.

Buus, S., Florentine, M., & Redden, R.B. (1982b). The SISI Test: A review. Part II. *Audiology, 21(5)*, 365-385.

Centers for Disease Control and Prevention (2009). Falls in Nursing Homes. Retrieved April 24, 2011, from http://www.cdc.gov/HomeandRecreationalSafety/Falls/nursing.html

Centers for Disease Control and Prevention (2010). Falls Among Older Adults: An Overview. Retrieved April 24, 2011, from http://www.cdc.gov/HomeandRecreationalSafety/Falls/adultfalls.html

Cornsweet, T.N. (1962). The stair-case method in psychophysics. *American Journal of Psychology, 75*, 485-491.

Desmond, A.L. (2004). Function and Dysfunction of the Vestibular System. In J. Berger & S. Liu (Eds.), *Vestibular Function: Evaluation and Treatment* (pp. 21-44). New York: Thieme Medical Publishers.

Dickins, J.R., Cyr, D.G., Graham, S.S., Winston M.E., & Sanford, M. (1992). Clinical significance of type 5 patterns in platform posturography. *Otolaryngology—Head and Neck Surgery, 107(1)*, 1-6.

Dix, M.R., & Hallpike, C.S. (1952). The pathology, symptomatology and diagnosis of certain common disorders of the vestibular system. *Proceedings of the Royal Society of Medicine, 45(6),* 341-354.

DiZio, P., & Lackner, J.R. (1990). Age differences in oculomotor responses to step changes in body velocity and visual surround velocity. *Journal of Gerontology, 45*, M89-M94.

Erber, N.P. (1982). *Auditory Training*. Washington D.C.: Alexander Graham Bell Association for the Deaf.

Evans, K.M., & Melancon, B.B. (1989). Back to basics: A discussion of technique and equipment. *Seminars in Hearing, 10*, 123-140.

Fineberg, R., O'Leary, D.P., & Davis, L.L. (1987). Use of active head movements for computerized vestibular testing. *Archives of Otolaryngology—Head and Neck Surgery, 113(10),* 1063-1065.

Furman, J.M., & Redfern, M.S. (2001). Effect of aging on the otolith-ocular reflex. *Journal of Vestibular Research, 11(2),* 91-103.

Gans, R.E., & Roberts, R.A. (2006). *VNG handbook: A clinical guide*. Seminole, FL: AIB Education Press.

Gans, R.E., & Yellin, M.W. (2007). Assessment of Vestibular Function. In B.

Brandenburg (Ed.), *Audiology Diagnosis* (2nd ed., pp. 540-566). New York: Thieme Medical Publishers.

Gianna, C., Heimbrand, S., & Gresty, M. (1996). Thresholds for detection of motion direction during passive lateral whole-body acceleration in normal subjects and patients with bilateral loss of labyrinthine function. *Brain Research Bulletin, 40*, 443-447.

Goldstein, E.B. (2010). Introduction to Perception. In J. Hague & J. Perkins (Eds.), *Sensation and Perception* (8th ed., pp. 3-22). Belmont, California: Wadsworth.

Goebel, J.A. (2001). The Ten-Minute Examination of the Dizzy Patient. *Seminars in Neurology, 21(4)*, 391-398.

Grabherr, L., Nicoucar, K., Mast, F.W., & Merfeld, D.M. (2008). Vestibular thresholds for yaw rotation about an earth-vertical axis as a function of frequency. *Experimental Brain Research, 186(4)*, 677-681.

Green, D.M., & Swets, J.A. (1966). *Signal Detection Theory and Psychophysics*. New York: Wiley & Sons.

Guttmann, C.R., Benson, R., Warfield, S.K., Wei, X., Anderson, M.C., Hall, C.B., et al. (2000). White matter abnormalities in mobility-impaired older persons. *Neurology, 54(6)*, 1277-1283.

Hagberg, J.M., Graves, J.E., Limacher, M., Woods, D.R., Leggett, S.H., Cononie, C., et al. (1989). Cardiovascular responses of 70- to 79-yr-old men and women to exercise training. *Journal of Applied Physiology, 66(6)*, 2589-2594.

Hall, J.W. (2008). *New Handbook of Auditory Evoked Responses*. Boston: Pearson Education.

Hamid, M.A., Hughes, G.B., Kinney, S.E., & Hanson, M.R. (1986). Results of sinusoidal harmonic acceleration test in one thousand patients: Preliminary report. *Archives of Otolaryngology—Head and Neck Surgery, 94(1)*, 1-5.

Handelsman, J.A., & Shepard, N.T. (2008). Rotational Chair Testing. In J.A. Goebel (Ed.), *Practical Management of the Dizzy Patient* (2nd ed., pp.137-152). Philadelphia: Lippincott, Williams, & Wilkins.

Hausdorff, J.M., Rios, D.A., & Edelber, H.K. (2001). Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Archives of Physical Medicine and Rehabilitation, 82*, 1050-1056.

Hirsch, B.E. (1986). Computed sinusoidal harmonic acceleration. *Ear and Hearing, 7,* 198-203.

Horak, F.B., Shumway-Cook, A., Crowe, T.K., & Black, F.O. (1988). Vestibular function and motor proficiency of children with impaired hearing, or with learning disability and motor impairments. *Developmental Medicine and Child Neurology, 30(1)*, 64-79.

Hosking, S., Evans, D., Embleton, S., Houde, B., Amos, J., & Bartlett, J. (2001). Hypercapnia invokes an acute loss of contrast sensitivity in untreated glaucoma patients. *British Journal of Ophthalmology, 85*, 1352-1356.

Hsu, L., Hu, H., Wong, W., Wang, S., Luk, Y., & Chern, C. (2005). Quality of life in elderly patients with dizziness: analysis of the Short-Form Health survey in 197 patients. *Acta Oto-Laryngologica*, *125*, 55-59.

Hudgins, C.V., Hawkins, J.E., Kaklin, J.E., & Stevens, S.S. (1947). The development of recorded auditory tests for measuring hearing loss for speech. *The Laryngoscope, 57(1)*, 57-89.

Hullar, T.E., Della Santina, C.C., Hirvonen, T., Lasker, D.M., Carey, J.P., & Minor, L.B. (2005). Responses of Irregularly Discharging Chinchilla Semicircular Canal Vestibular-Nerve Afferents During High-Frequency Head Rotations. *Journal of Neurophysiology, 93*, 2777-2786.

Hunter, L.L., & Balzer, G.K. (1991). Overview and introduction to dynamic platform posturography. *Seminars in Hearing, 12(3)*, 226-237.

Ishiyama, G. (2009). Imbalance and Vertigo: The Aging Human Vestibular Periphery. *Seminars in Hearing, 29(5)*, 491-499.

Jacobson, G.P., & Newman, C.W. (1993). Background and technique of caloric testing. In G.P. Jacobson, C.W. Newman, & J.M. Kartush (Eds.), *Handbook of balance function testing* (pp. 156-192). St. Louis: Mosby-Year Book.

Jacobson, G.P., Newman, C.W., & Peterson, E.L. (1993). Interpretation and usefulness of caloric testing. In G.P. Jacobson, C.W. Newman, & J.M. Kartush (Eds.), *Handbook of balance function testing* (pp. 193-233). St. Louis: Mosby-Year Book.

Johnsson, L.G. (1971). Degenerative changes and anomalies of the vestibular system in man. *Laryngoscope, 81(10)*, 1682-1694.

Kingdom, F.A.A., & Prins, N. (2010). *Psychophysics: A Practical Introduction*. London: Academic Press.

Leek, M.R. (2001). Adaptive procedures in psychophysical research. *Perception and Psychophysics, 63(8),* 1279-1292.

Leigh, R.J., & Zee, D.S. (1991) *The neurology of eye movements*. New York: Oxford University Press.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49(2),* 467-477.

Li, C.W., Hooper, R.E., & Cousins, V.C. (1991). Sinusoidal harmonic acceleration testing in normal humans. *Laryngoscope, 101(2)*, 192-196.

Lim, D.J. (1984). Otoconia in health and disease. A review. *The Annals of Otology, Rhinology, and Laryngology: Supplement, 112*, 17-24.

Lindeman, H.H. (1969). *Studies on the morphology of the sensory regions of the vestibular apparatus*. New York: Springer.

MacMillan, N.A., & Creelman, C.D. (2005). *Detection Theory: A User's Guide*. Mahwah, New Jersey: Lawrence Erlbaum Associates.

MacNeilage, P.R., Banks, M.S., DeAngelis, G.C., & Angelaki, D.E. (2010). Vestibular heading discrimination and sensitivity to linear acceleration in head and world coordinates. *Journal of Neuroscience, 30(27)*, 9084-9094.

Maes, L., Dhooge, I., D'haenens, W., Bockstael, A., Keppler, H., Philips, B., et al. (2010). The Effect of Age on the Sinusoidal Harmonic Acceleration Test, Pseudorandom Rotation Test, Velocity Step Test, Caloric Test, and Vestibular-evoked Myogenic Potential Test. *Ear and Hearing, 31(1),* 84-94.

Mallery, R.M., Olomu, O.U., Uchanski, R.M., Militchin, V.A., & Hullar, T.E. (2010). Human discrimination of rotational velocities. *Experimental Brain Research, 204(1),* 11-20.

Mallinson, A.I., & Longridge, N.S. (2004). Caloric response does not decline with age. *Journal of Vestibular Research, 14*, 393-396.

Masin, S.C., & Fanton, V. (1989). An explanation for the presentation-order effect in the method of constant stimuli. *Perception and Psychophysics, 46(5)*, 483-486.

Meredith, C.N., Frontera, W.R., Fisher, E.C., Hughes, V.A., Herland, J.C., Edwards, J., et al. (1989). Peripheral effects of endurance training in young and old subjects. *Journal of Applied Physiology, 66(6),* 2844-2849.

Merfeld, D.M., Park, S., Gianna-Poulin, C., Black, F.O., & Wood, S. (2005a). Vestibular perception and action employ qualitatively different mechanisms. I. Frequency response of VOR and perceptual responses during Translation and Tilt. *Journal of Neurophysiology, 94(1)*, 186-198.

Merfeld, D.M., Park, S., Gianna-Poulin, C., Black, F.O., & Wood, S. (2005b). Vestibular perception and action employ qualitatively different mechanisms. II. VOR and perceptual responses during combined Tilt and Translation. *Journal of Neurophysiology, 94(1)*, 199-205.

Micromedical Technologies (2004). Thresholds for the System 2000 Rotational Chair.

Mulch, G., & Petermann, W. (1979). Influence of age on results of vestibular function tests: Review of literature and presentation of caloric test results. *The Annals of Otology, Rhinology, and Laryngology: Supplement, 56*, 1-17.

Nachmias, J., & Steinman, R.M. (1965). An experimental comparison of the method of limits and the double staircase-method. *American Journal of Psychology, 78,* 112-115.

Nasher, L.M. (1971). A model describing vestibular detection of body sway motion. *Acta Otolaryngologica, 72(6)*, 429-436.

Nasher, L.M., & Peters, J.F. (1990). Dynamic posturography in the diagnosis and management of dizziness and balance disorders. *Neurologic Clinics, 8(2)*, 331-349.

Neuhauser, H., Leopold, M., von Brevern, M., Arnold, G., & Lempert, T. (2001). The interrelations of migraine, vertigo, and migrainous vertigo. *Neurology, 56(4)*, 436-441.

Park, J.J., Tang, Y., Lopez, I., & Ishiyama, A. (2001). Age-related changes in the number of neurons in the human vestibular ganglion. *The Journal of Comparative Neurology, 431(4)*, 437-443.

Ochi, K., & Ohashi, T. (2003). Age-related changes in the vestibular-evoked myogenic potentials. *Otolaryngology—Head and Neck Surgery, 129(6),* 655-659.

Paige, G.D. (1991). The aging vestibulo-ocular reflex (VOR) and adaptive plasticity. *Acta Otolaryngologica Supplement, 481*, 297-300.

Pearson, J.D., Morrell, C.H., Gordon-Salant, S., Brant, L.J., Metter, E.J., Klein, L.L., et al. (1995). Gender differences in a longitudinal study of age-associated hearing loss. *Journal of the Acoustical Society of America, 97(2)*, 1196-1205.

Pradhan, P.L., & Hoffman, P.J. (1963). Effect of spacing and range of stimuli on magnitude estimation judgments. *Journal of Experimental Psychology, 66,* 533-541.

Reske-Nielsen, E., & Hansen, C.C. (1964). Pathological Studies in Perceptive Deafness: Four Patients with Presbyacusis. *Acta Otolaryngologica, 57*, 327-330.

Roeser, R.J., & Clark, J.L. (2007). Pure-Tone Tests. In B. Brandenburg (Ed.), *Audiology Diagnosis* (2nd ed., pp.238-260). New York: Thieme Medical Publishers.

Rosenhall, U. (1973). Degenerative patterns in the aging human vestibular neuro-epithelia. *Acta Otolaryngologica, 76*, 208-220.

Sadeghi, S., Chacron, M.J., Taylor, M.C., & Cullen, K.E. (2007). Neural Variability, Detection Thresholds, and Information Transmission in the Vestibular System. *Journal of Neuroscience, 27(4)*, 771-781.

Schuknecht, H.F. (1964). Further Observations on the Pathology of Presbyacusis. *Archives of Otolaryngology—Head and Neck Surgery, 80(4),* 369-382.

Shimizu, K., Murofushi, T., Sakurai, M., & Halmagyi, G. (2000). Vestibular evoked myogenic potentials in multiple sclerosis. *Journal of Neurology, Neurosurgery, and Psychiatry, 69(2)*, 276-277.

Thalmann, R., Ignatova, E., Kachar, B., Ornitz, D., & Thalmann, I. (2001). Development and maintenance of otoconia: biochemical considerations. *Annals of the New York Academy of Sciences, 942*, 162-178.

Thibodeau, L.M. (2007). Speech Audiometry. In B. Brandenburg (Ed.), *Audiology Diagnosis* (2nd ed., pp.288-313). New York: Thieme Medical Publishers.

Tomonaga, M. (1977). Histochemical and ultrastructural changes in senile human skeletal muscle. *Journal of the American Geriatrics Society, 25(3)*, 125-131.

Van der Laan, F.L., & Oosterveld, W.J. (1974). Age and vestibular function. *Aerospace Medicine, 45(5)*, 540-547.

von Brevern, M., Radtke, A., Lezius, F., Feldmann, M., Ziese, T., Lempert, T., et al. (2007). Epidemiology of benign paroxysmal positional vertigo: a population based study. *Journal of Neurology, Neurosurgery, & Psychiatry, 78(7)*, 710-715.

Voorhees, R.L. (1989). The role of dynamic posturography as a screening test in neurotologic diagnosis. *Laryngoscope, 99(10)*, 995-1001.

Wall, C., Black, F.O., & Hunt, A.E. (1984). Effects of Age, Sex, and Stimulus Parameters upon Vesibulo-ocular Responses to Sinusoidal Rotation. *Acta*

Otolaryngologica, 98, 270-278.

Watanuki, K., & Schuknecht, H.F. (1976). A Morphological Study of Human Vestibular Sensory Epithelia. *Archives of Otolaryngology—Head & Neck Surgery, 102*, 583-588.

Welgampola, M.S., & Colebatch, J.G. (2001). Vestibulocollic reflexes: Normal values and the effect of age. *Clinical Neurophysiology, 112*, 1971-1979.

Whitman, G.T., Tang, T., Lin, A., & Baloh, R.W. (2001). A prospective study on cerebral white matter abnormalities in older people with gait dysfunction. *Neurology, 57*, 990-994.

Wright, C.G., & Schwade, N.D. (2007). Anatomy and Physiology of the Vestibular System. In B. Brandenburg (Ed.), *Audiology Diagnosis* (2nd ed., pp. 65-76). New York: Thieme Medical Publishers.

Yost, W.A. (2000). *Fundamentals of Hearing: An Introduction* (5th ed.). San Diego: Academic Press.

Zapala, D.A., & Brey, R.H. (2004). Clinical experience with the vestibular evoked myogenic potential. *Journal of the American Academy of Audiology, 15(3)*, 198-215.

Zapala, D.A., Olsholt, K.F., & Lundy, L.B. (2008). A comparison of water and air caloric responses and their ability to distinguish between patients with normal and impaired ears. *Ear and Hearing, 29(4)*, 585-600.